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PERFORMANCE EVALUATION OF SBS MODIFIED ASPHALT MIXTURES USING WARM MIX TECHNOLOGIES

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PERFORMANCE EVALUATION OF SBS MODIFIED ASPHALT MIXTURES USING WARM MIX TECHNOLOGIES

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ABSTRACT

The need for more sustainable methods and techniques in the asphalt paving industry has been increasing and it is important to respond to the needs of society and address issues surrounding its environment and health. In order to better introduce such new and more sustainable methods, it is necessary to combine existing and proven methods with new technology. The main idea of this research was to use the established industry standards of using styrene butadiene styrene (SBS) modified asphalt mixtures and combine it with the relatively new warm mix asphalt (WMA) technology in order to create a more sustainable and eco-friendly asphalt paving process. Two WMA technologies, micro water (Aspha-min) and synthetic wax (Sasobit) based, were used to evaluate their effectiveness in SBS modified asphalt mixtures along with binders. The four major areas of research included the binder analysis (including Superpave binder performance and surface topography); compaction condition study; oxidative aging analysis and mixture performance analysis.

The general findings were that the WMA additives especially improved the binder properties at higher temperatures namely viscosity and rutting and the inclusion of these materials did not adversely affect the engineering properties of the mixtures. Atomic Force Microscopy (AFM) was utilized to obtain the various surface images that showed the strong correlations with especially aging process. The compaction condition study showed that WMA mixtures had better compaction behavior under lower temperatures and gyrations and also the other volumetric results indicated the comparability with the hot mix asphalt (HMA) mixtures. The oxidative aging results showed that the asphalt

mixtures aged in the oven had a higher level of aging than the binder by itself aged in the rolling thin film oven (RTFO). Also, the benefit of using WMA technologies (reduced aging) can be accomplished by using lower aging condition.

DEDICATION

I dedicate this dissertation to my mother, Sookyeol Choi, and my father, Kiwon Kim. They are the ones worthy of this degree, because of the way they lovingly and sacrificially supported me.

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TABLE OF CONTENTS

Table of Contents (Continued)

Page

LIST OF TABLES

Table Page

List of Tables (Continued)

Page

List of Tables (Continued)

Page

List of Tables (Continued)

Page

List of Tables (Continued)

Page

LIST OF FIGURES

Figure Page

List of Figures (Continued)

Page

CHAPTER ONE

INTRODUCTION

Background

Sustainability, according to the U.S. Environmental Policy Act, involves the creation and maintenance of conditions under which humans and nature can exist harmoniously, while fulfilling social and economical requirements. These requirements include the reduction of emissions and the alleviation of its effects on human health and the environment. The effects of industry on its surroundings have been widely broadcasted and several agencies have been formed to monitor and limit these effects. According to one of these agencies, the Environmental Protection Agency (EPA), overall total industrial emissions in the U.S. have risen over 17% from 1990 to 2007 and it is expected to continue to increase at 1% per annum. The EPA states that this increase is strongly influenced by a rise in population, economic growth, the fluctuating price of energy, technological changes and many other factors.

The paving industry has its own share of emission concerns with its use of hot mix asphalt (HMA), with the major source coming from the production facility. HMA plants, regardless of its manufacturing technique (drum or batch) emit between 56,000 lbs/yr and 83,000 lbs/yr, depending on their fuel type (natural gas, oil etc) (USEPA 2000). These emissions contain substances such as reactive organic gases (ROGs) and particulate matter (PM). The ROGs emitted involve a wide cross section of contaminants including volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOC's) including polynuclear aromatic hydrocarbons (PAHs), aromatics and

aliphatics. They (ROGs) also play a key role in smog formation and visibility degradation. Particulate matters (PM) often referred to as aerosols, are of particle sizes fewer than 2.5 to 10 microns and are often adhered to by ROGs. These particles affect air quality because they can be irreversibly trapped in the pulmonary tract (NPI 1999, Kitto et al. 1997).

One of the latest technologies of the asphalt industry is Warm Mix Asphalt (WMA), which can lower plant and field operation temperatures. The temperature reduction of 19 ~ 56°C (35 ~ 100°F) is the key idea behind WMA, resulting in the reduction of production cost, energy, and most importantly pollutant emissions. This is accomplished using diverse techniques such as organic/chemical additives, emulsions, material/plant foaming, and synthetic binders (Kim et al. 2010; Croteau and Tessier 2008; You and Goh 2008; Suttmeier 2006). It also has several practical advantages including better compaction for stiff mixes, longer storage and cool weather paving. Several federal government organizations (e.g., Federal Highway Administration (FHWA), state departments of transportation, and the EPA) are currently strongly promoting this new technology (Cater 2008; Kantipong et al. 2008; Jones 2006).

Although WMA is a relatively new technology to the United States' paving industry, it has a history in Europe as being one of the green technology responses to the Kyoto accord. In a push to reduce emissions and lower the temperature of HMA, the first European experiments with WMA took place in 1995 with the first pavements coming soon after. The National Asphalt Pavement Association (NAPA) first brought WMA technology to the United States from Europe in 2002, creating strong interest among

HMA producers and contractors. This technology was then demonstrated at the World of Asphalt in 2004 and the first US trials were carried out in Florida and North Carolina in the same year, with a material foaming technique (Brown 2008; Newcomb 2008; Prowell 2007b).

The FHWA designated WMA as a focus area. In 2005 they collaborated with NAPA and formed a WMA Technical Working Group to oversee WMA investigations and field trials in the United States. Initial research was conducted by the National Center for Asphalt Technology (NCAT) on WMA technologies and their findings were published through 2005/2006. In 2007, the FHWA sent a team of material experts to Europe to evaluate the effects of the previously used WMA technologies. They discovered that a range of technologies were available to produce WMA and they believed that although there were a few areas that need to be addressed, the technology was still viable and the paving industry needed to continue to pursue the current path (VaitKus 2009; D'Angelo et al. 2008; Corrigan 2006; Hurley and Prowell 2005a, b and 2006; Prowell 2007a).

Since this declaration, research interest has grown dramatically, with many studies conducted on both the local and federal levels. Research has been ongoing in the form of various field trials, laboratory experiments and the development of new WMA technologies. Like any new technology, new questions will arise to challenge its validity, especially when it represents a change from established methods to newer techniques. These challenges and questions can be met and answered with continued methodical research and rigorous testing.

While seeking to improve the quality of asphalt pavements, the asphalt industry developed polymer modified asphalts (PMA) to help to meet the demand for better pavements and to influence better pavement performance under high traffic applications. Polymer modifications are becoming important factors in paving industry due to their proven effects such as better resistance to rutting, fatigue damage, stripping, and thermal cracking in asphalt pavements (Wekumbura et al. 2007; Punith 2005; Chen et al. 2003). Of the polymer modifiers, styrene butadiene styrene (SBS) originally developed by Shell Chemical Co. is widely used in the majority of the asphalt binder industry and probably the most appropriate polymer for asphalt modification (Lavin 2003; Becker et al. 2001; Wen et al. 2001). SBS creates a three dimensional network within virgin asphalt phase, resulting in excellent bonding strength to aggregates which leads to a durable and long lasting pavement (Kim 2003; Adedeji et al. 1996).

However, according to Newcomb in 2006 and Illinois DOT in 2005, there have been difficulties in workability of PMA because of the high viscosity of the modified binders. A common response for the above issue is to increase the production and placement temperatures to achieve a desired density at site. Other issues related to the use of the PMA can be focused to following areas (Daranga 2005; Roque et al. 2005; Budija et al. 2004; Zubeck et al. 2003):

- Concern about the continuous exposure of workers to high temperatures during paving operations which may yield significant health problems;
- Concern about the health issues that will also arise from the high levels of toxic fumes;

- While working at elevated temperatures, the polymer can be thermally degraded and may not perform to its full potential and
- A higher economical cost due to the increased fuel consumption.

Significance of Work

The relationship between widely used methods and new technologies must be for the benefit of society. Such a relationship can be formed between the commonly used SBS modified asphalt and the newer WMA technologies. In the past, to reap the benefits of SBS binder modification, the industry practiced methods that were not always environmentally sound and economically friendly. However, societal culture has changed throughout the years and now there is a greater demand for quality and especially sustainability. These demands cannot be ignored and therefore a new approach must be considered. Currently, there is limited information on the use of WMA technology in SBS modified asphalt mixtures. It is because of the great potential to bring about sustainability with the use of this technology, that a thorough study of its relationship be implemented.

The purpose of this was to investigate the relationship between WMA technologies as it related to alleviating the environmental issues surrounding SBS modified asphalt mixtures. The emphasis then, was to study the effect of SBS modified asphalt mixtures using WMA technologies at lower temperatures. Initially, the selected binder tests were employed to obtain general information regarding SBS modified binder containing WMA additives. The main focus, apart from general binder information, was

on experiments involving mixture and temperature. One important issue was to determine the effects of compaction conditions at different gyration levels and temperatures. Another task was to evaluate the oxidative aging level, that is, how much the aging can be delayed by lowering the temperatures of WMA technologies. Mixture performance analysis was then carried out with regard to laboratory mixture test modes.

The conclusions from the present study may be of interest to the asphalt industry, which still has questions regarding this new technology. It is important to develop a firm understanding of the performance of the combining of SBS and WMA. Informative research may perhaps answer these questions and influence the industry to accept the new technology. The unique objectives of this research, which has not been previously investigated, can serve as a benchmark for further research into asphalt sustainability and as the groundwork for the creation of a new standard of WMA paving operations.

Research Objectives

The main objective of this study was to investigate the effects of WMA technologies on the performance properties of SBS modified asphalt mixtures along with binders. The specific objectives included following:

1. Conducting an extensive review of literature on WMA and polymer modified asphalt;
2. Investigating the selected binder properties such as viscosity, rutting, fatigue cracking, and thermal cracking and topography;

3. Investigating the relationship between volumetric properties and compaction conditions;
4. Investigating the oxidative aging levels; and
5. Investigating the selected mixture properties such as rutting, moisture sensitivity, temperature sensitivity, and long-term aging.

Scope of Research

The objectives of this study were accomplished through the completion of the tasks described below:

1. Conducting the binder analysis through Superpave binder testing methods and microscopic method:
   a) Rotational viscometer (ASTM D 4402, AASHTO T 316)
      - Viscosity at 135°C to determine the ability for pumping, coating, placing of asphalt binder
   b) Dynamic shear rheometer (DSR) (ASTM D 7175, AASHTO T 315)
      - High failure temperature to determine the ability for the resistance of permanent deformation (or rutting)
      - Fatigue cracking property at 25°C
   c) Bending beam rheometer (BBR) (ASTM D 6648, AASHTO T 313)
      - Thermal cracking property at -12°C
   d) Two types of aging simulations were used in laboratory
      - Rolling thin film oven (ASTM D 2872) for short-term aging condition
      - Pressure aging vessel (ASTM D 6521) for long-term aging condition
   e) Atomic Force Microscopy (AFM)
      - Surface imaging (Micro in area and Nano in height) in air with tapping mode

2. Conducting the mix design and compaction condition study through the following procedures:

   a) Superpave mix design

   - Preparing the cylindrical specimens (D = 150 mm) using a Superpave gyratory compactor for measuring volumetric properties (AASHTO T 312) and the loose samples for measuring maximum specific gravity using vacuum with vibrator (ASTM D 2041)
   - Determining the optimum asphalt content (OAC) at 4% air void

   b) Compaction condition study

   - Two main elements (compaction level and temperature effect)
     - Compaction levels at two temperatures
       - WMA at 135℃ (25, 50, 75, and 100 gyrations)
       - HMA at 154℃ (25, 50, 75, and 100 gyrations)
     - Temperature effects at two compaction levels (25 and 100 gyrations)
       - WMA (154, 135, 118, and 96℃)
       - HMA (154, 135, 118, and 96°C)
   - Determining volumetric properties including air voids (%), bulk density (g/cc), voids in mineral aggregate (%), and voids filled with asphalt (%) with respect to effect of compaction levels and temperatures.

3. Evaluating the oxidative aging levels through the following procedures:

   a) Short-term oven aging (STOA)

   - Preparing the loose samples (mineral aggregate coated with asphalt binders)
   - Aging the samples in the oven under four conditions (135°C and 154℃ both for 2h, 4h)

   b) RTFO aging

   - At two temperatures (163°C and 135℃ both for 85 min)

   b) Oxidative aging analysis based on large molecular size (LMS)

   - Using High-pressure gel permeation chromatography (HP-GPC)

- Measuring the material's LMS from STOA and RTFO methods

4. Evaluating the mixture performance through following tests:
   a) Moisture sensitivity at 7% air void (as per SC-T-70)
   b) Rutting resistance at 64℃ (as per AASHOTO TP 63)
   c) Resilient modulus at 5, 25, and 40℃ (as per ASTM D 7369)
   d) Long-term property at 4% air void (ITS after oven aging under 100℃, 2days)

Organization of Dissertation

This dissertation is divided into six chapters of which chapter I introduces the problem and provides the background information. The significance of this body of research is also presented along with its objectives and scope. Chapter II explores the characteristics of polymer modified asphalt along with the types of WMA technology, its sustainability and its national experience. Chapter III provides information regarding the materials and experimental procedures involved in the research process. The statistical analysis methods used to evaluate the test results are provided in Chapter IV. Experimental results and discussions are presented in Chapter V and finally, a summary, conclusion and recommendations for further study are presented in Chapter VI.

CHAPTER TWO

REVIEW OF LITERATURE

Polymer Modified Asphalt

For many years, polymers have been incorporated into asphalt as a way to mitigate the major causes for asphalt pavement failures, including permanent deformation at high temperatures and cracking at low temperatures (Chen et al. 2002; Li et al. 1998). This polymer modified asphalt (PMA) binder also has been used with success at locations of high stress such as interstates, intersections, and airports (Yildirim 2007). It has proven itself to be another essential element in the paving process.

When a polymer and virgin asphalt are blended, the polymer strands absorb part of the low molecular weight oil fraction of the virgin asphalt and become swollen. When the polymer-rich phase becomes the continuous phase (due to the relatively higher fraction of swollen polymer), the swollen strands connect together and form a three dimensional network. This network provides the physical properties of elasticity, plasticity, and elongation of asphalt binder (Wekumbura at el. 2007). Ultimately, PMA binders become more viscous and tend to improve the binder coating (i.e., by increasing its film thickness) on aggregates and this holds the aggregate particles together more effectively. These properties result in a greater performance of the pavement (Illinois DOT 2005).

There are several types of polymers used in asphalt binders today, currently, the most commonly used polymer for asphalt modification is the SBS (styrene butadiene styrene) followed by other polymers such as crumb rubber, SBR (styrene butadiene

rubber), EVA (ethylene vinyl acetate) and polyethylene (Sengoz and Isikyakar 2008). In the United States, the SBS is the choice used frequently. According to a modified asphalt market survey in 2005-2006, 80% of states across the country used SBS as a modifier (Casola 2006).

SBS behaves like elastic rubbers at ambient temperature and it can be processed like plastics when heated (thermoplastic elastomer). Generally, most types of rubber are difficult to process because they are cross-linked, however, SBS and other thermoplastic elastomers can be managed to be rubbery without being cross-linked, thus making them easy to process into useful shapes. In structural terms, its backbone chain is made up of three segments as shown Figure 2-1 (Rajpal 2005). Polystyrene is a hard plastic which provides durability at high temperature, while butadiene is a rubber which contributes to the elasticity of the binder at low temperature. Figure 2-2 shows a schematic of the interaction between the SBS network and the asphalt fractions (Shull 1995). It is envisioned that the SBS network interacts with the asphaltene and resin micelles (Rozeveld et al. 1997).

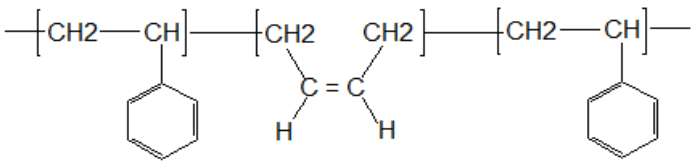


Figure 2-1: Basic structure of SBS polymer

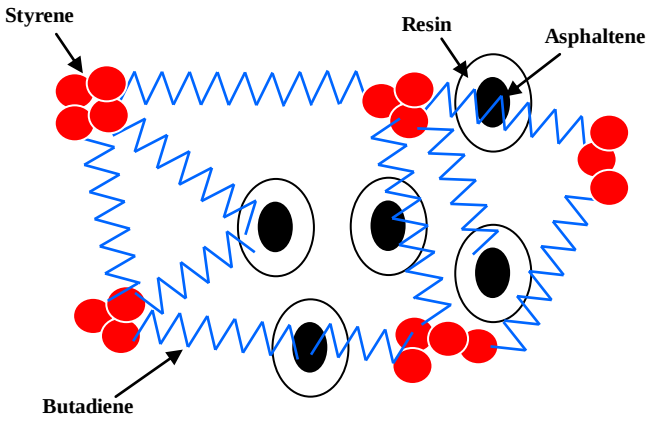


Figure 2-2: A schematic of the SBS interaction with asphalt fractions

Although the use of polymer modification is shown to greatly improve the performance of virgin asphalt, possible problems can occur during paving operations. In general, asphalt mixtures produced with PMA binders are mixed and compacted at a higher temperature, because of their higher viscosity properties, than conventional mixtures. Furthermore, the polymers can be destroyed by the temperature being too high during mixing or by being held at an elevated temperature for a long period of time after mixing (Roque et al. 2005). However, with lower mixing and compaction temperatures, the PMA mixtures might result in several problems such as inadequate volumetric properties (i.e., high air voids) and poor short-term and long term performance. From late 1993 until early 1995, a number of Australian road contractors reported unacceptably high levels of "fume" evolution during placement when PMA binders were used. Health problems described by some road crews, presumably caused by the fumes, included vomiting, nausea, headaches, sore throats and sore eyes. Most of the problems were observed to be experienced when the SBS was used as a modifier (Budija et al. 2004).

WMA Technology

One answer can be found with Warm Mix Asphalt (WMA) technology as a method of reducing the heat requirement for pavement operations whilst at the same time maintaining the integrity of the PMA binder. The major principles of producing WMA are described in this section with the main focus being in decreasing the viscosity within the production and compaction range. The range of operation temperatures within WMA is between 93°C to 135°C while HMA production usually runs 135°C to 163°C (Button et al. 2007).

WMA technology can be classified either by the proprietary products of various organizations or by the equally proprietary processes developed by professionals throughout the years. Company products fall under the larger title of organic additives, some of which are shown in Table 2-1. Under the category of chemical additives there are also several choices; two of which are presented in Table 2-2. Separately, Table 2-3 lists examples of foaming processes that can achieve temperature reduction using an additive or plant equipment modifications (Chowdury and Button 2008; D'Angelo et al. 2008; Romier et al. 2006; Hurley and Prowell 2005a, b and 2006; Astec Inc; Eurovia Services; Sasol Wax)

Table 2-1: Organic Additives

Product name (*Company*)	Description
Sasobit (*Sasol*)	• It is one of the end products from Fischer –Tropsch (FT) process where synthesis gas (coal gasification is an important source) is reacted in the presence of a catalyst. • The wax is completely melted in asphalt binder at temperatures greater than 116℃, resulting in the viscosity reduction of asphalt binder. • This reaction allows the mixing with aggregates and compaction at the lower temperature of 30℃ than HMA. • It has been pre-blended with the asphalt binder at the dosage rate of 1.0~1.5% by weight of binder in United States.
Asphaltan - B (*Romonta*)	• It is a refined wax (Montan) that is blended with a fatty acid amide. Montan wax is found in brown coal deposits that have been formed due to fossilized sub tropical vegetation. • It s melting point is approximately 99℃ and dosage rate is about 2.5% by weight of binder. • Like FT waxes, it supports the improved flow of asphalt.
Licomont BS (*Clariant*)	• It is a fatty acid amide which is produced by the reaction of amines and fatty acids. • Its melting point is between 141 and 146℃ and dosage rate is about 3% by weight of binder. • Used in asphalt binder as a viscosity modifier.

Table 2-2: Chemical Additives

Product name (*Company*)	Description
Evotherm (*MeadWestvaco*)	• It is a chemical package that includes cationic emulsification agents that improve the aggregate coating, mixture workability and compaction. • The package is diluted with a little water and introduced to the asphalt line before mixing.
Rediset (*Akzo Nobel*)	• It is a proprietary chemical additive that comes in a pellet solid form designed as a warm mix additive with adhesion promotion properties. • It is added to the binder at 1-2% by weight of binder.

Table 2-3: Foaming Processes

Product name (*Company*)	Description
Aspha-min (*Eurovia*)	• It is a synthetic zeolite powder that contains 21% micro water in crystalline form and is added to the mix shortly before or at the same time as the binder at a rate of 0.3% by total weight of the mix. • The water is gradually released during the mixing process in the temperature range of 85°C to 182°C causing a slight increase of binder volume (foaming effect).
LEA (*Fairco et al*)	• It is a process that uses the moisture contained in the aggregates to foam the asphalt. • Coarse aggregate and asphalt are heated at regular temperature then mixed with wet fine aggregate (3% moisture). • This process causes the moisture to turn to steam thus causing the asphalt on the coarse aggregate to foam.
LEAB (*BAM*)	• It is a commercialization of a half warm foam mix that uses a series of six nozzles to produce this product. • An amine based additive is added at 0.1% by weight of binder immediately prior to foaming to aid in foam stabilization.
WAM-Foam (*Kolo Veidekke et al*)	• It is a collaboration system where two different grades of binders (soft and hard) introduce at different times in the mixing cycle during production. • The aggregates are first mixed with the soft binder which is fluid enough at a lower temperature and then the entire mixture is combined with the hard binder. • The hard binder is infused with a small quantity of cold water to induce foaming.
Double Barrel Green (*Astec*)	• It uses a multi-nozzle foaming device to produce WMA. • A computer controlled system adjusts the number of nozzles used based on the production rate. • About 1lb of cold water is introduced through the nozzles per ton of mix causing the binder to expand by about 18 times.

WMA Sustainability

The idea of sustainability deals with practices that have a positive influence on the environmental, social and economical aspects of human life circumstances. The environmental concern deals with reduction of heat generation, toxic byproducts and the emission of greenhouse gases. Social concerns have its focus on improved working conditions, higher quality work and increased productivity. The economical aspect looks

at reduction of material and fuels costs and reduced maintenance of existing structures. Since those involved in asphalt production are always looking to increase the performance of their product, they are constantly examining new technologies that may realize these goals and at the same time recognize the object of sustainability. It is also important to note that sustainable development is interchangeable and does not only focus on one particular aspect; energy conservation for example, requires construction efficacy and promotes environmental and social development since there is a strong correlation among the categories. Table 2-4 demonstrates those three aspects of sustainability as it relates to the use of WMA technology in the asphalt pavement area (D'Angelo et al. 2008; Chowdhury and Button 2008; Button et al. 2007; Prowell 2007; Kristjandottir et al. 2007; Kristjandottir 2006; Koenders et al. 2000).

National Experience of WMA

Recognizing the importance of the sustainability concerns of society, and the possible advantages for employing WMA technology in its various forms, many institutions across the United States have carried out various studies and experiments to evaluate its effectiveness under certain conditions. Extensive collaborations have been done all over the country to produce laboratory demonstrations and test warm mix performance. Many states in the US have conducted WMA field experiments with approximately 200 projects and field trial sections around the country since 2004. Tables 2-5 and 2-6 show descriptions of some of the major laboratory experiments and field demonstrations that have been documented and some of which are still in progress (Xiao

and Amirkhanian 2009; Mallick and Bergendahl 2009; Kirk 2009; Akisetty 2008; Anderson et al. 2008; Al-Rawashdeh 2008; Boggs 2008; Cliff 2008; Chowdhury and Button 2008; Colorado DOT 2008; Gandhi 2008; Goh and You 2008; Jones et al. 2008; Mallick et al. 2008; You and Goh 2008; Wasiuddin et al. 2007 and 2008; Prowell et al. 2007; Hurley and Prowell 2005a, b and 2006).

Table 2-4: WMA Sustainability

Category	Demonstration
Environmental & Social Friendly	• Data indicate plant emissions can be significantly reduced up to 70% depending on the kinds of pollutants such as greenhouse gases (CO_2) and traditional gaseous pollutants (CO, NO_x, and SO_2). • WMA technology decreases the heat of the mixture and the emissions of volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs) which improve the safety and working environment of workers. • There are no visible white fumes in both the plant and the paving site with WMA usage decreasing societal anxiety with apparent pollution. • Less dust is produced due to lower temperature and shorter heating time. • These environmental benefits may yield easy permission to build the plant site in urban areas.
Energy Conservation	• Burner operation cost (fossil fuel and electricity) is efficiently saved by using WMA ranging from 20 to75% depending on how much production temperature is lowered. • New pavement materials can be more easily conserved by using higher RAP percentages because the viscosity reduction of WMA can be similar to using a soft binder grade effect, allowing stiffer mixes.
Construction Efficiency	• Low viscosity has a lubricating role, resulting in better workability and compactibility with less effort. • Paving can be extended to cooler weather conditions (i.e., winter or night) while desired density is still obtained. • Less hardening of binder during construction could give more flexibility and resistance to cracking in service, thus improving longevity of pavement life. • Lower temperature capacity is gives the ability to store or haul materials over a longer time with less heat loss to the mix while maintaining workability. • This benefit can extend market areas and decrease mobilization cost. • Thermal segregation is minimized in the mat due to lower cooling rate. • WMA provides earlier open to traffic where is beneficial (i.e., intersection).

Table 2-5: Laboratory study

Organization	Description
NCAT	• The first to conduct laboratory research on WMA technology around 2005/2006 (Hurley and Provell) and produced 3 reports on Aspha-min, Sasobit and Evotherm. • It was reported that all of these technologies improved compactibility in the Superpave Gyratory Compactor in temperatures as low as 190℉. • The resilient moduli of the mixes were not affected by the implementation of the three technologies. • Lower mixing and compaction temperature increases rutting potential due to lessened binder aging and increases moisture sensitivity due to incomplete drying of aggregate. • However, the addition of anti-stripping agents helped these issues.
Clemson University	• In 2008, Akisetty and Gandhi reported experiments using Aspha-min and Sasobit in both a control mix and a rubberized asphalt mix. • It was discovered that operation temperatures can be reduced with the application of these WMA technologies. • These WMA additives were seen not to have an effect on the mechanical properties (rutting, moisture sensitivity, and resilient modulus) of both mixes. • Xiao and Amirkhanian (2009) carried out ITS tests using moist aggregate with the same WMA additives. • It was reported that ITS values were influenced by aggregate moisture content and the addition of those additives into the mix did not alter that fact.
University of Oklahoma	• Wasiuddin et al (2007) conducted experiments using Aspha-min and Sasobit using dosage rates or 2,3 and 4 percent. • It was found that the higher dosage rates reduced the mixing temperatures by up to 16℃ for a PG 64-22 binder and to 13℃ for PG 70-28 binder. • The rutting potential decreased, it was found, with the decreased mixing and compaction temperature. • In a separate study in 2008, the same researchers looked at the effect of WMA binders (Sasobit and Aspha-min) on wettability and adhesion. • A general trend was found where Sasobit decreased the adhesion between binder and aggregate whilst Aspha-min showed no change or an increase in adhesion depending on PG grade.
Michigan Technological University	• You and Goh (2008) carried out dynamic modulus testing using Aspha-min. • No affect on the dynamic modulus (E*) value was discovered regardless of the mixture types. • Using MEPDG predictions, however, it was found that rut depths were reduced up to 48% over 20 years.

Table 2-5: (Continued)

Organization	Description
Worcester Polytechnic Institute	• Mallick et al (2008) carried out a study to determine the effects of a WMA additive (Sasobit) with 75% RAP. • The results showed that it was possible to produce WMA mixes with high percentages of RAP that had air void contents comparable to that of HMA. • Furthermore, the addition of a significantly lower grade binder produced WMA mixes that were most comparable with HMA. • Mallick and Bergendahl (2009) conducted a CO_2 emission study using WMA. • Temperature was found to be only statistically significant factor on the emission. • The use of Sasobit (1.5%) was a very effective way of lowering the emission (greater than 30% reduction).

Table 2-6: Field experience

Organization	Description
NCAT	• Prowell et al (2005) conducted a study for two WMA test sections of the NCAT test track to assess the rutting performance using Evotherm as the WMA additive. • The WMA section showed excellent rutting performance (about 1mm) after exposure to about half a million ESALs, a result comparable to the HMA performance. • WMA surface layers showed equal or better in-place densities as compared to the HMA section. • Lower fuel consumption and no visible fumes were observed during construction.
Caltrans	• Jones et al (2008) constructed a test track (80m by 8.0m) with the aim of discovering whether the use of WMA additives to reduce the operation temperatures of asphalt concrete would influence the mix's performance. • The target mix production temperatures were achieved during WMA section construction (Sasobit, Evotherm, and Zeolite); lower than those of HMA. • Rutting performance was not significantly influenced by the WMA technology when evaluated with the Heavy Vehicle Simulator. • Paving crew interviews indicated that no problems were experienced with lower temperature and no haze or smoke was observed on the WMA construction. • Additionally, lower temperature operations and procedures did not affect the quality of the final pavement. • California (2009); California DOT constructed two WMA pavement sections in I-5 Fresno and Merced counties; the first using Astec Double Barrel Green and the second a combination of Double Barrel Green with Evotherm. Cores were taken and various tests will be conducted in this ongoing study.

Table 2-6: (Continued)

Organization	Description
Other States	• Florida (2004); a demonstration project was constructed using Aspha-min and this yielded a 19°C reduction in operation temperatures. Furthermore, cores taken after 1 year showed no evidence of moisture damage when compared to control samples (Government engineering 2007). • Indiana (2005); Evotherm was first used to produce 660 tons of WMA with 15% RAP for a county road. Generally, various WMA construction advantages were observed. • Texas (2006); Texas DOT placed their first warm mix asphalt trial using the Evotherm process on Loop 368 in San Antonio. All test sections are performing well as at this time. TxDOT is still in the progress of evaluating short and long term performance. • South Carolina (2007); Boggs paving, Inc. demonstrated Astec Double Barrel Green with 50% RAP (Rock Hill, SC). Rutting evaluation was done at Clemson University from cores taken ; it showed less than HMA rutting values. • Colorado (2008); CDOT constructed a WMA pavement section on I-70 to test the pavement's performance under severe cold weather. Under these conditions, early WMA performance was seen to be equal to that of HMA. Useful performance data is anticipated in 2010. • Ohio (2008); Ohio DOT constructed a test pavement on Rt 541 using WMA technology (Sasobit, Evotherm, and Aspha-min) with SBS modified binder (PG 70-22) and 15% RAP. Relatively lower air void content was observed when compared to the HMA section. Cores were taken up to twelve months after construction and they revealed that the tensile strength of the Evotherm sample remained consistent with that of the HMA whilst the tensile strength of the Aspha-min and Sasobit samples decreased steadily with time.

Discussion of Literature Review

The literature review showed a strong focus on proving the effectiveness of WMA as a technology, not only for the industry, but also with regard to sustainability. The concentration was thus on field and laboratory testing in order to determine how it measures up to the results of the existing HMA methods. This body of work, although in its preliminary stages, shows indeed some promising results as for the technology of WMA. Even though there is ongoing discussion on the WMA properties discovered in laboratory testing, the field testing that has been carried out within the past few years has

yielded no negative performance issues to date. In 2007, Button et al, noted that although the test tracks had been active for only 5 years, it was their experience that signals of distress would have exhibited themselves within that period.

The advantages of SBS polymers, comes with great concerns in the area of energy conservation and health related issues. Keeping this in mind, new or existing technologies such as WMA can be combined with SBS modified asphalt mixture to reduce its harmful effects. The new trend in society is not only to develop new technologies, but also to keep them environmentally friendly and reduce whatever effects they have to its general health and well being. Zettler in 2006 stated that there is still a long way to go before the technology is widely utilized in the United States. The pavement industry on a whole is slow to accept new technologies and therefore more comprehensive research is needed to prove the superiority of WMA and its application compared to HMA (Chowdhury et al. 2008). The concerns of Newcomb in 2006 and Illinois DOT in 2005 and Duranga, Budija and Zubeck et al especially, have implied and perhaps inspired the need for research into polymers and WMA.

CHAPTER THREE

MATERIALS AND EXPERIMENTAL PROCEDURES

This chapter describes a more detailed insight of the materials and procedures (i.e., plans and methods) used throughout this research process. The information presented contains details on materials (e.g., asphalt binders, aggregates, and WMA additives), experimental plans and the test methods employed in this research work.

Materials

Asphalt binders

Three polymer modified asphalt (PMA) binders containing styrene butadiene styrene (SBS) (3% by weight of each binder) were used in this study. Table 3-1 shows the properties and image of typical SBS modifier used for asphalt modification. The performance grade (PG) of each binder was PG 76-22, which is commonly applied to the surface course of the higher traffic zone (i.e., interstate or intersection). The base binders had different sources and they included a mixture of several crude sources (referred to as I), a Venezuelan source (II), and a Middle Eastern source (III). Table 3-2 shows the results of the standard binder testing.

Table 3-1: Properties and image of a typical SBS modifier

Properties		Image
Physical state	Solid	
Color	White or Natural	
Odor	Essentially odorless	
Density (kg/m^3)	880-950	
Solubility (in water)	Insoluble	
Specific gravity	< 1	

Table 3-2: Properties of SBS modified binders used in this study

Testing conditions			Binder sources		
Temperature	Properties	Aging	I	II	III
135°C	Viscosity (Pa-s)	**U**	1.537	2.139	1.428
76 °C	G*/sin δ (kPa)	**U**	1.382	1.702	1.163
	G*/sin δ (kPa)	**R**	2.579	4.498	2.558
25 °C	G*sin δ (kPa)	**P**	4,167	2,880	1,775
-12°C	Stiffness (MPa)	**P**	175	133	126
	m-value	**P**	0.301	0.336	0.333

Note: **U**, Unaged; **R**, RTFO aged; **P**, RTFO + PAV aged

Aggregates

Two aggregate sources, classified as granite (type A) and marble schist (type B), obtained from different locations were used in this research. Type B, which contained a

higher concentration of calcium (CaO = 19.9%), provides better resistance to stripping than type A (CaO = 3.2%). However, a typical state DOT may not have many choices of aggregate types due to availability and cost constraints (Caro et al., 2008; Copeland 2007; Huang et al., 2005; Jahromi 2009). Approximately 82% of transportation agencies in the US recommend the use of anti-stripping additives to prevent moisture damage. The South Carolina DOT specifies the use of hydrated lime as an anti-stripping agent (Putman and Amirkhanian 2006).

Table 3-3 shows the properties of each type of aggregate used in this study. Both quarries crush and hold the aggregate as four specific sizes (i.e., No. 67, No. 789, regular screening (RS), and manufactured screening (MS)). Each categorized aggregate was placed in the buckets and transported to the laboratory. In addition, hydrated lime (1% by weight of aggregate) in a slurry form was also used in this study as an anti-strip additive. The proportion of these materials was adjusted to meet the Superpave gradation of a nominal maximum size (12.5 mm). Figure 3-1 shows this combined gradation of each aggregate type.

Table 3-3: Properties of aggregate types A and B used in this research

	Specific gravity			Soundness (%)	Absorption (%)	LA abrasion (%)	Fineness Modulus
	Bulk Dry	Bulk SSD	Apparent				
Type A	2.67	2.72	2.77	0.1	1.1	46	2.82
Type B	2.77	2.78	2.82	0.6	0.7	32	2.81

Note: Type A – Granite (Igneous rock), Type B – Marble schist (Metamorphic rock).

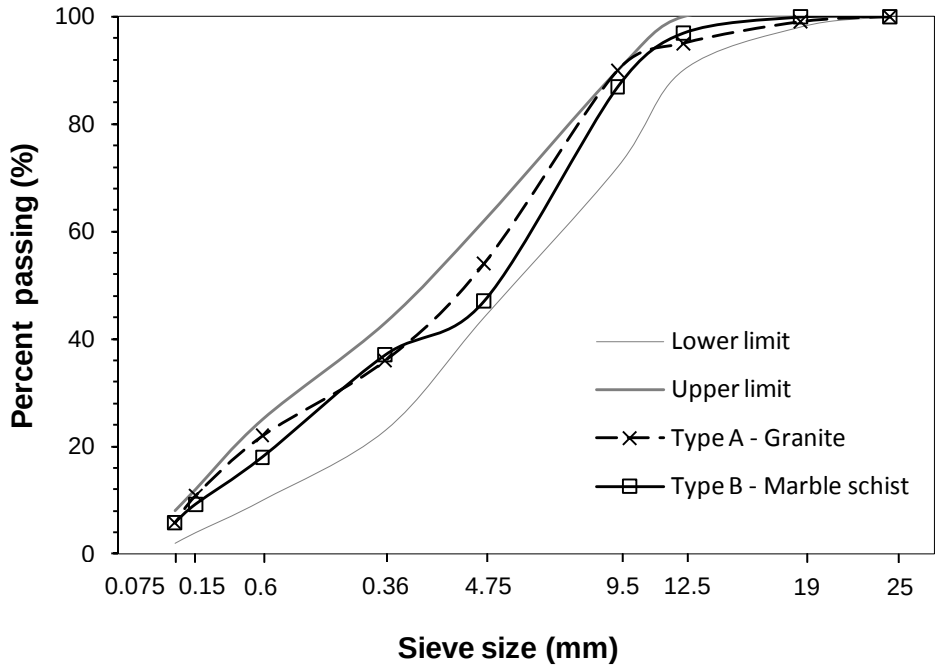


Figure 3-1: Combined aggregate gradation

WMA additives

Two types of WMA technologies (i.e., micro water based and organic wax based) were used in this study. The first is a synthetic zeolite powder, Aspha-min, manufactured by Eurovia Services. It contains about 21% micro water in crystalline form and is added to the mix shortly before or at the same time as the binder at a rate of 0.3% by total weight of mix. The water is gradually released during mixing process in the temperature range of 85°C to 182°C, causing a slight increase of binder volume (foaming effect). Gradual release of water provides the comfortable workability over a longer period of 6 to 7 hours at lower temperatures. The temperatures of production and construction can be reduced as much as 30°C using this method (Hurley and Prowell 2005).

The second is a Fischer-Tropsch (FT) wax, Sasobit, manufactured by Sasol Wax. It is one of the end products from the FT process where synthesis gas (coal gasification is an important source) is reacted in the presence of a catalyst. The wax is completely melted in an asphalt binder at temperatures greater than 116°C, resulting in the viscosity reduction of asphalt binder. This reaction allows the mixing with aggregates and compaction at a lower temperature (i.e., 30°C) than HMA. It has been pre-blended with the asphalt binder at the dosage rate of 1.0~1.5% by weight of binder in the United States. At service condition, it forms a crystalline network in the binder which represents the structural stability (D'Angelo et al. 2008). Figure 3-2 shows the images of these WMA additives.

(a) (b)

Figure 3-2: Images of (a) Aspha-min and (b) Sasobit additives

Experimental Plan

The research process involved the completion of four distinct tasks which include binder analysis, compaction condition study, oxidative aging analysis and mixture

performance analysis. The materials used in each task are shown in Table 3-4 and the processes for these tasks are outlined in the paragraphs and flow charts following. Three binder sources (Task 1) were selected since they are heavily used in the market place. For Superpave mix design and mixture performance analysis (Tasks 2 and 4), binder sources I and II and aggregate sources A and B were used because of consistent successful use in previous research and a more intimate knowledge of their behavior. For the compaction condition study (Task 2), the focus was more on the aggregate properties, which have a greater influence on the volumetric properties than binder source; therefore, the most frequently used binder source in South Carolina was employed. For the oxidative aging analysis, previous research has shown that different binder sources influence aging behavior. Thus to clearly see such differences, all three binder sources were used with only one randomly selected aggregate source. Two WMA additives (Aspha-min and Sasobit) were constantly used in each task.

Table 3-4: Materials used in each task

		Binder source	Aggregate source	WMA additive
Task 1	Binder Analysis	I, II, and III		Both additives in each task
Task 2	Superpave Mix Design	I and II	A and B	
	Compaction Condition Study	I	A and B	
Task 3	Oxidative Aging Analysis	I, II, and III	A	
Task 4	Mixture Performance Analysis	I and II	A and B	

Task 1: Binder Analysis

The first task, shown in Figure 3-3, was for quantifying the asphalt's performance based on the Superpave binder specification and the test methods. These simulate the three critical stages during the binder's life: in its original state, after mixing and construction, and after in-service aging. This process helps to distinguish the performance of SBS modified binders as they are combined with different WMA additives. Furthermore, supplementary information regarding the binder's changing topography based on binder sources and WMA additives was collected via AFM.

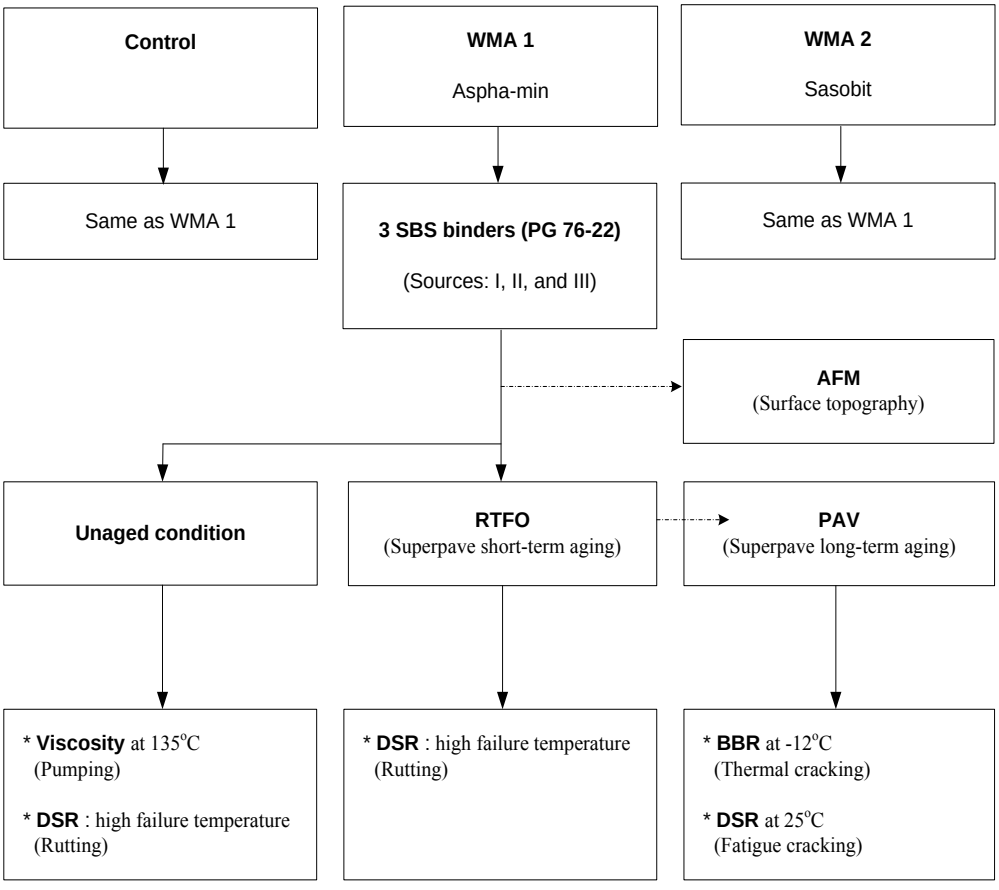


Figure 3-3: Flow chart for the Superpave binder test

Task 2: Mix Design and Compaction Condition Study

The second task involved the Superpave gyratory compactor (SGC) which produces asphalt mix specimens that are similar to pavement densities achieved under traffic loads and climate conditions. This task was done by two sub tasks, (shown in Figures 3-4 and 3-5) including the Superpave mix design for mainly determining the optimum asphalt content (OAC) and the compaction condition study as functions of levels and temperatures. The OAC values were used in the production of all testing samples throughout this research and more importantly, compaction condition study carried out to show the different volumetric properties between HMA and WMA mixtures.

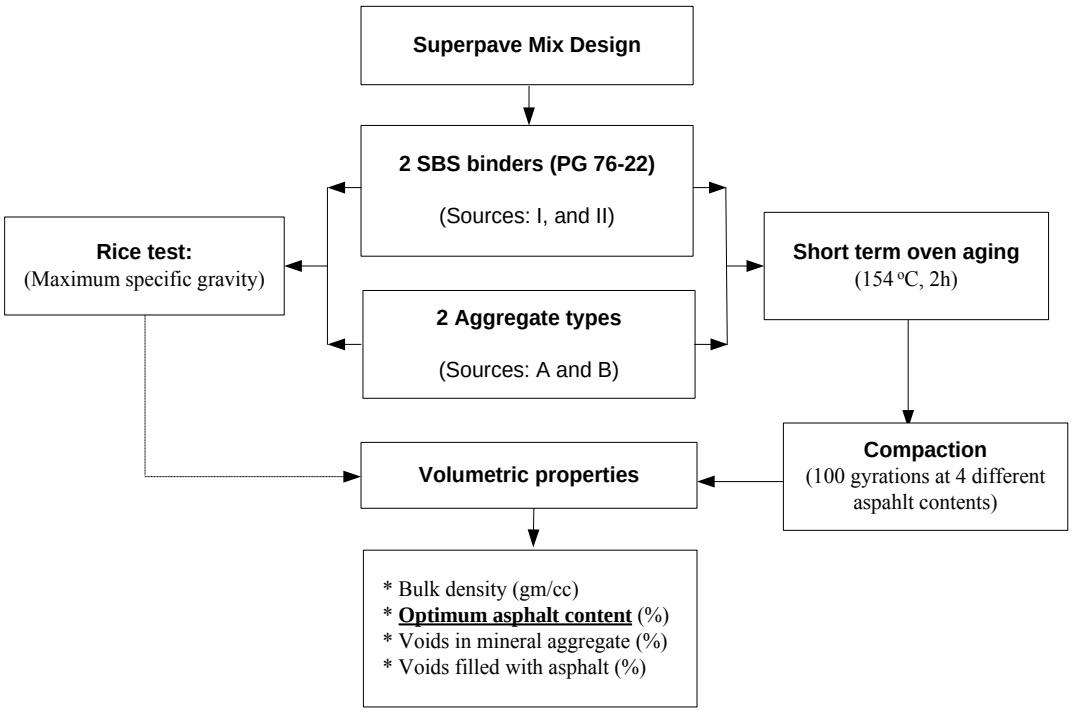


Figure 3-4: Flow chart for the Superpave mix design

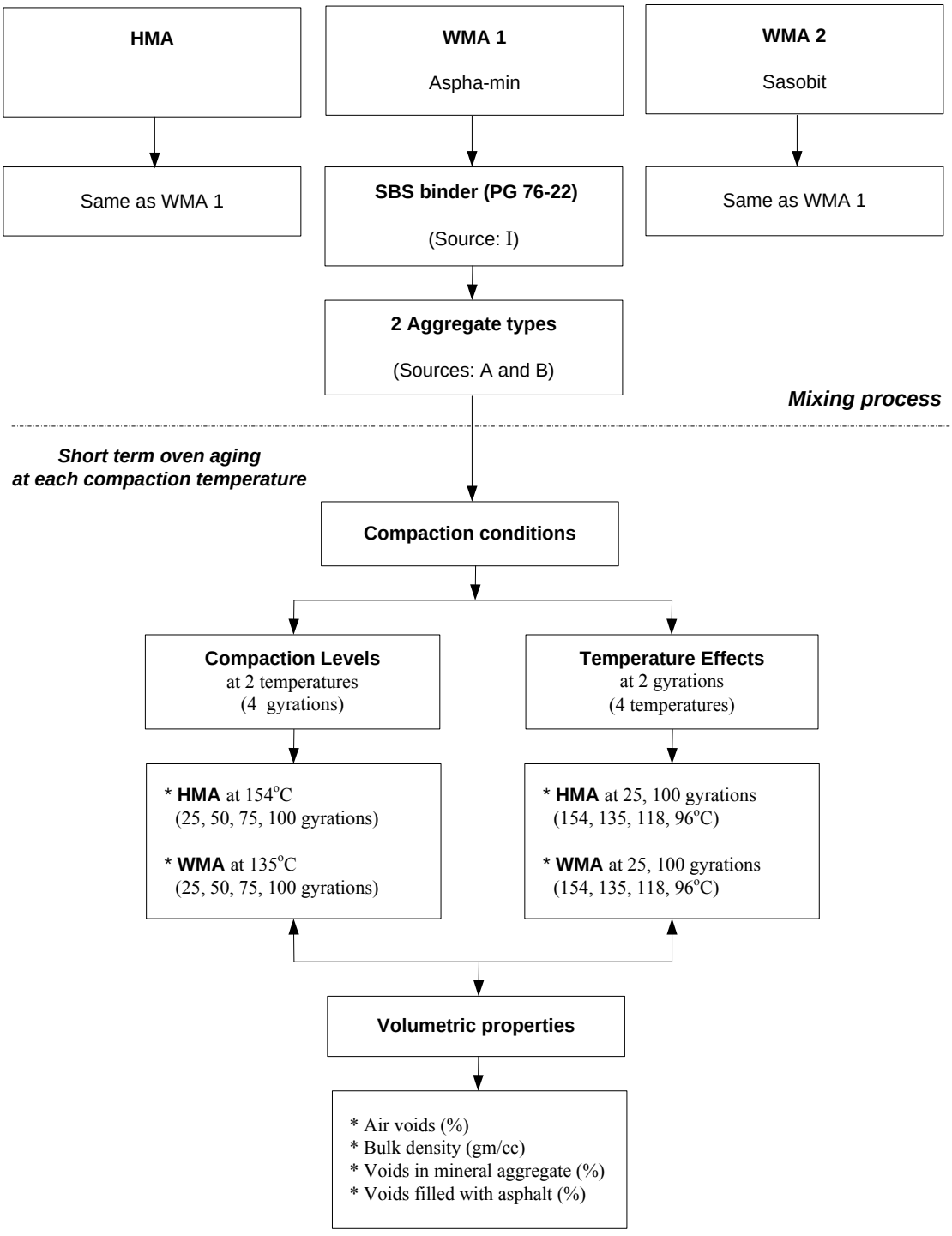


Figure 3-5: Flow chart for the compaction condition study

Task 3: Oxidative Aging Analysis

Aging for the short-term period is simulated by using rolling-thin film oven (RTFO) for asphalt binders and short-term oven aging (STOA) for asphalt mixtures in the laboratory. However, there are potential limitations in both aging processes including (Li and Nazarian 1995):

- Aging of asphalt binder alone is not a sufficient indicator because of the fact that asphalt-aggregate interaction is not simulated and
- Considerable efforts are required to identify the aging susceptibility of asphalt mixtures.
- There is no established method of determining the aging level of the binder in the mixes before and after the STOA.

An alternative technique, High-pressure gel permeation chromatography (HP-GPC or GPC), can be used to overcome these issues. An advantage of using GPC is that the dissolved asphalt binders in tetrahydrofuran (THF) solution from the selected particles of asphalt mixtures can be used as a test sample. This means that this method can be adapted to evaluate the oven aging effect of asphalt mixtures using various sample curing conditions (Lee et al, 2009; Kim et al. 2006). The third task thus, shown in Figure 3-6, was to investigate the oxidative aging effects of SBS modified asphalt mixtures made with WMA technologies using GPC based on its large molecular size (LMS). The LMS values were compared (1) among the STOA conditions, (2) between the RTFO conditions, and (3) both aging conditions.

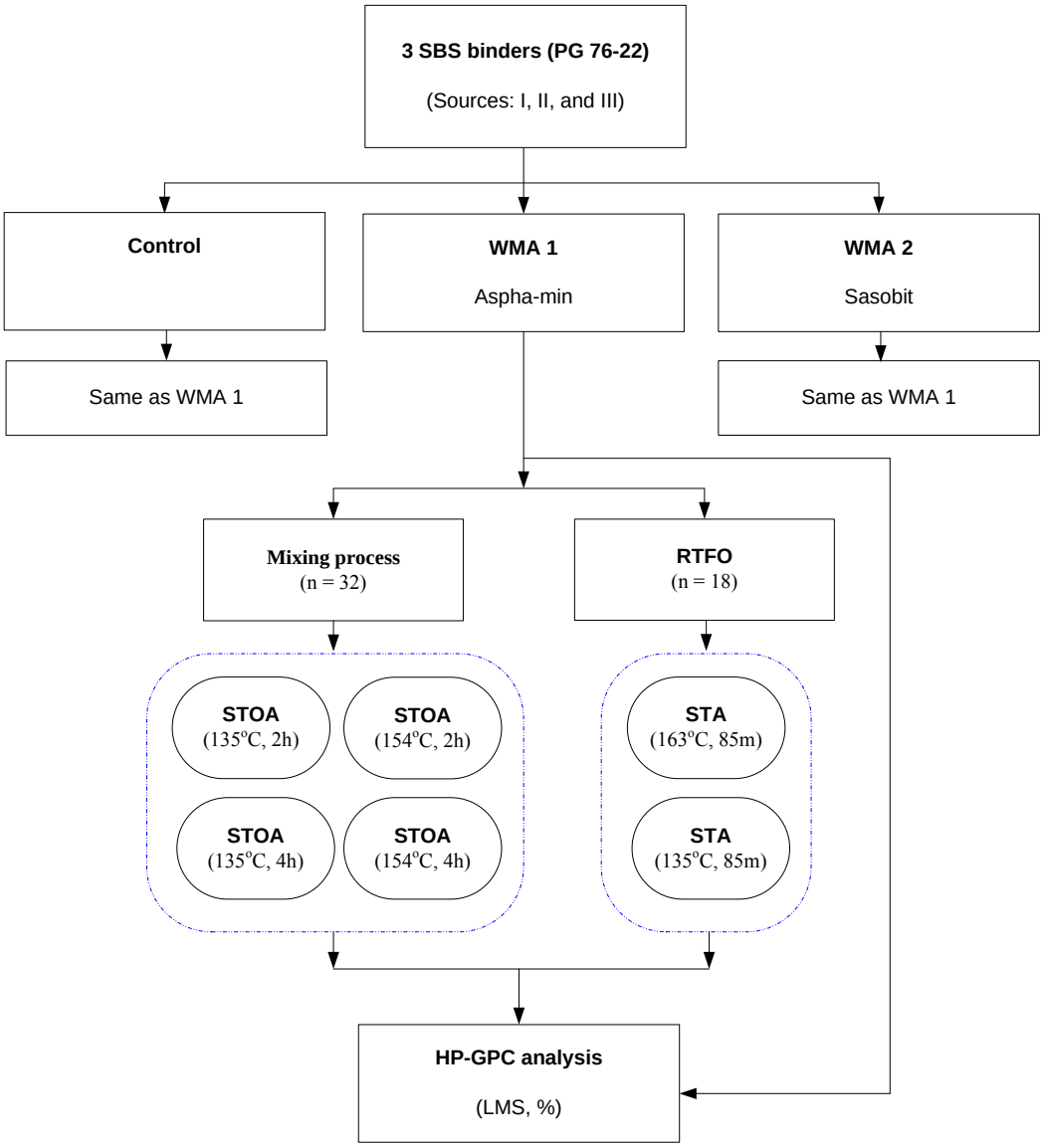


Figure 3-6: Flow chart for the oxidative aging analysis

Task 4: Mixture Performance Analysis

The last task, shown in Figure 3-7, was to investigate the mixture performance of SBS modified asphalt mixtures incorporating the WMA technologies. SBS modified binders from two different sources were used to fabricate the SBS modified asphalt mixtures incorporating the two WMA technologies (Aspha-min and Sasobit). Laboratory mixture test modes including rutting, moisture sensitivity (indirect tensile strength, ITS), resilient modulus (temperature sensitivity), and one of the long-term properties (ITS after oven aging) were then carried out.

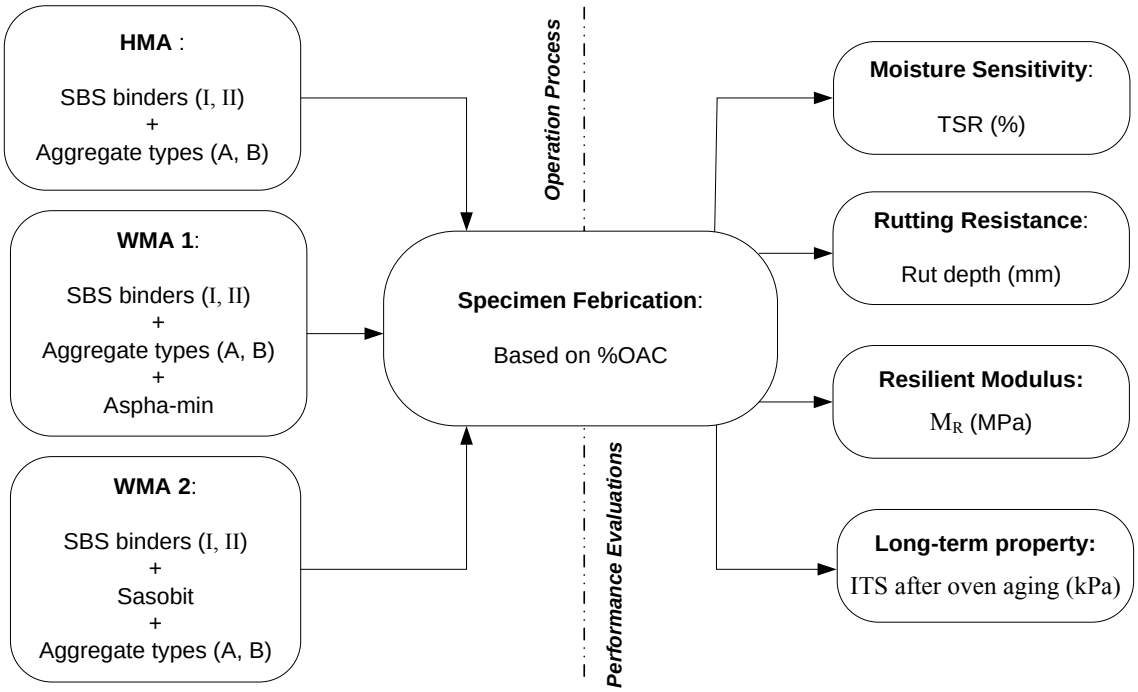


Figure 3-7: Flow chart for the mixture performance analysis

Test Methods

Binder Sample Preparation

Two types of addition processes of the WMA additives into SBS modified binders or mixtures were used. Process 1 involved the addition of Aspha-min via manual blending. The concentration used was 5% by binder weight recommended by the manufacture (0.3% by mix weight – a binder content of 6% was assumed). It was added to the SBS modified binders, heated at 150°C and blended by manual stirring to disperse thoroughly. Process 2 involved the addition of Sasobit via mechanical blending. Approximately 1.5% by binder weight was added into the SBS modified binders and blended with a mechanical mixer at 150°C for 5 minutes (Gandhi and Amirkhanian 2007). Binder aging processes were then conducted by rolling thin film oven (RTFO) for 85 minutes at 163°C (ASTM D 2872) and pressure aging vessel (PAV) for 20 hours at 100°C (ASTM D 6521).

Superpave Binder Testing

The selected Superpave binder test procedures included the viscosity test (as per AASHTO T 316), the bending beam rheometer (BBR) test (as per AASHTO T 313), and the dynamic shear rheometer (DSR) test (as per AASHTO T 315). Three replicate samples were tested and the results were reported as the average of these tests.

A 10.5 gram binder sample was tested with a number 27 spindle in the rotational viscometer at 135°C. In the DSR test, the binders (Original, RTFO residual, and PAV residual) were tested at a frequency of 10 radians per second, which is equal to

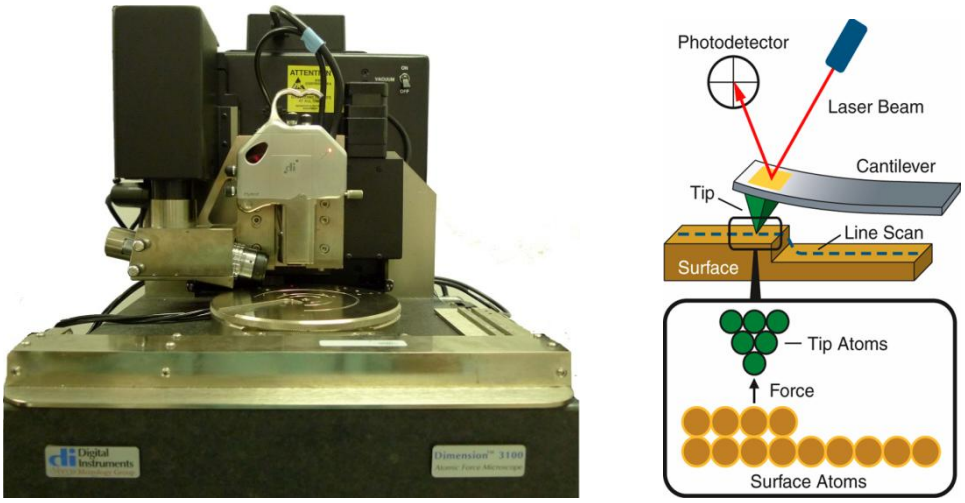
approximately 1.59 Hz. The BBR test was conducted on asphalt beams (125 × 6.35 × 12.7 mm) at -12°C, and the creep stiffness (S) and creep rate (*m*) of the binders were measured at a loading time of 60 seconds.

Atomic Force Microscopy

Atomic Force Microscopy (AFM) is a form of nanotechnology in which a cantilever and probe with a nano sized tip (2-10 nm) scans the surface of a material to clearly define its topography. There are two major modes of operation when using this technology, contact and tapping; the latter was used in this study. TappingMode is advantageous because it removes the shear stress present, making it easier to image soft, fragile and adhesive surface without damage (Russel and Batchelor 2004; Blanchard 1996). TappingMode oscillates the cantilever and probe at the sample surface. The atoms of the tip lightly touch the atoms of the sample surface while the scan is being performed and they only touch at the bottom of each oscillation (Figure 3-8 (b)). As the tip touches the surface, a laser beam deflects in a regular pattern over a photo detector array, generating a sinusoidal, electronic signal which is processed as surface imaging in the equipment.

Figure 3-8 (a) shows the AFM (The Digital Instruments / Veeco Dimension 3100) equipment used during this study. A total of 9 binder samples (each of the three SBS modified binder sources with two WMA additives) were prepared for this testing. Each heated sample was poured into a DSR silicone mold, then removed and placed on a thin plastic film. This was the only preparation required for AFM testing. The calibration

(laser adjustment and tip attachment) was done according to the instructions presented in the user manual for this model and the AFM software (NanoScope Version 5) managed the operation of the cantilever and probe and recorded the images of the sample surfaces. The scan dimensions were 20 × 20 μm × 50 nm with a scan rate of 0.996 Hz and a resonant frequency of 75 kHz.



(a) (b)

Figure 3-8: (a) Atomic Force Microscopy and (b) its principle

Superpave Mix Design

Surface course type A of South Carolina Department of Transportation (SC DOT) specifications was selected for Superpave mix design. This is designed for the higher traffic zone (e.g., interstate) and has three requirements which include 12.5 mm of nominal maximum aggregate size, PG 76-22 of modified binders, and 100 gyrations of compaction. The procedures described in AASHTO T 312 (standard method of test for

preparing and determining the density of HMA specimens by means of the Superpave gyratory compactor) were followed for preparing specimens in this study. Operation temperatures (i.e., mixing and compaction) from the recommendations of the binder providers were followed. Each of the optimum asphalt contents (OACs) was obtained at the target air void (4.0%) and other volumetric properties (i.e., VMA, VFA, and bulk density) were also calculated and checked. The mix design results were also used when WMA mixtures were fabricated (Hurley and Prowell 2005a, b) and these operation temperatures were 19 ~ 28℃ less than the binder provider's recommendations.

Compaction Condition Study - (1) Temperature Effects

For this study, the mixing temperatures used were at 163℃ (325°F) for HMA and at 143℃ (290°F) for WMA. The SBS modified asphalt mixtures were oven aged at four compaction temperatures, (96, 118, 135, and 154°C) for two hours. This range was selected based on the temperatures 135 and 154℃, which are commonly used as short-term oven aging temperatures in the laboratory to simulate binder aging and absorption during the construction of HMA pavements (Asphalt Institute 2003). The compaction temperatures of 96 and 118℃ were selected to evaluate the effect of WMA additives at relatively lower temperatures. The specimens were fabricated to the two target air void contents of 7±1% and 4±1% using 25 and 100 gyrations of SGC, respectively. Each specimen was 150 mm in diameter and 115±5 mm in height. A total of 96 specimens (3 binder types × 2 aggregate sources × 4 compaction temperatures × 2 compaction levels × 2 repetitions) were prepared and their volumetric properties were measured.

Compaction Condition Study - (2) Compaction Levels

The loose mixtures were oven-aged at 154°C and 135°C for HMA and WMA mixtures, respectively. The compaction was carried out as a function of compaction level. The five compaction levels in SGC were 25, 50, 75, and 100 gyrations. This range was chosen to produce the target air void contents from 4±1% to 7±1%. A total of 48 specimens (3 binder types × 2 aggregate sources × 4 compaction levels × 2 repetitions at each compaction temperature) were prepared and their volumetric properties were measured.

Oxidative Aging Analysis - (1) Sample Preparation

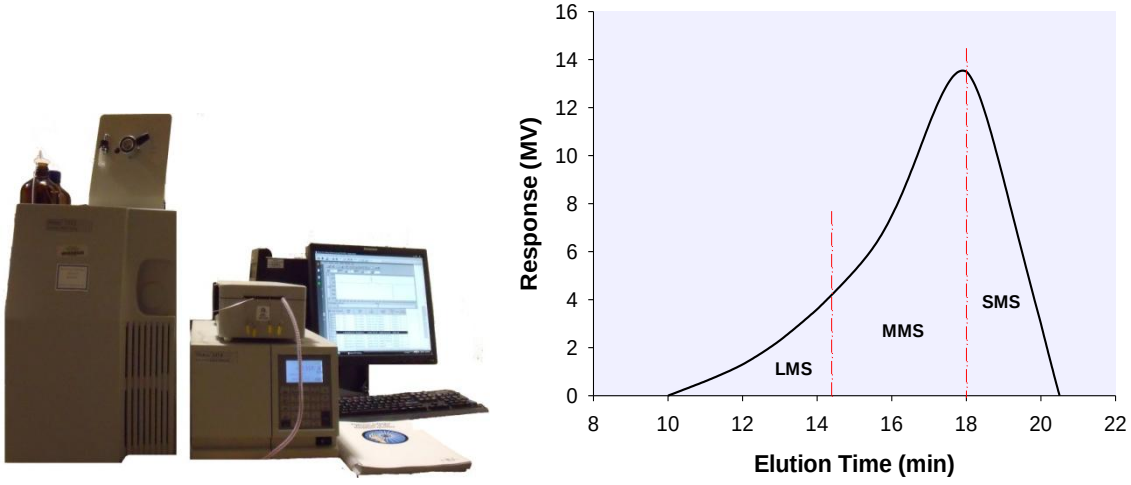
A total of 18 loose mixtures (9 binder types × 1 aggregate source (type A) × 2 oven aging temperatures) were prepared and each sample was taken to evaluate the aging caused by the mixing process and aged in the oven by:

- Recommended oven aging condition (154°C for 2 hours);
- Alternative oven aging condition (154°C for 4 hours);
- Reduced oven aging conditions (135°C for 2 and 4 hours).

For comparison purposes, all binders were also separately aged using the RTFO at 135°C for 85 min for the reduced aging condition and the RTFO at 163°C for 85 min for the Superpave standard condition.

Oxidative Aging Analysis - (2) GPC Procedure

The Waters GPC equipment with computerized software was used for chromatographic analysis of binders (Figure 3-9 (a)). A differential refractive index meter (Waters 410) was used as a detector. A series of two columns (Waters HR 4E and HR 3) was used for separating constituents of asphalt binder by molecular size. The specification of the columns is shown in Table 3-5. For testing the samples at a constant temperature, the columns were kept at 35°C throughout the test in a column oven. The mobile phase was a tetrahydrofuran (THF) flowing at a rate of 1 ml/min. The concentration rate used was 0.5% by weight of binder. This rate was recommended by the manufacturer of the equipment.



(a) (b)

Figure 3-9: (a) GPC system and (b) its typical chromatogram

Table 3-5: Pore size and effective molecular weight range

Column	External length (cm)	Pore size (Å)	Effective molecular weight range (ps)
Styragel HR 3	30	1,000	500~30,000
Styragel HR 4E	30	Mixed bed	50~100,000

Each binder sample dissolved into THF was filtered through a 0.45 μm syringe filter prior to injection into the injection module. A sample volume of 50 μl was injected into GPC injector for each test. One test took 30 min and elution started at approximately 11 min from injection and ended at approximately 21 min, as shown in Figure 3-9 (b). Testing for each sample was repeated three times and then the average value of the large molecular size (LMS) portion was reported.

Oxidative Aging Analysis - (3) Sampling Method

For this analysis, GPC tests were carried out using two sampling methods. For aged mixtures, a selected amount of the mixture sample passing the 4.75 mm sieve was collected and placed into THF solvent. Since THF is a polar solvent, the binder in the mixture was dissolved in 5 minutes with some manual shaking effort. To keep the concentration of the dissolution in all testing the same, 0.5% by weight, the binder content of the mix had to be obtained. The ignition oven test (as per AASHTO T 308-04) was used to measure the binder content for the mixture passing 4.75 mm sieve. For aged binders, the specified quantity of binder was randomly collected and was dissolved in THF at the same concentration rate (0.5% by weight). The concentration of the binder in

the solvent was achieved by dissolving a binder sample of 0.008 gram in a THF solvent of 3.2 grams.

Oxidative Aging Analysis - (4) For GPC Result

In Figure 3-9 (b), the area under the curve represents 100% of the binder molecules injected into the GPC system (Kim et al. 2004). The asphalt binder constituents are generally classified into several groups (Jennings 1980; Jennings and Prabanic 1983; Kim et al. 1995; Noureldin and Wood 1989). In this study, a chromatogram profile was partitioned into 13 slices and three parts: large molecular size (LMS; slices 1 to 5), medium molecular size (MMS; 6 to 9) and small molecular size (SMS; 10 to 13) (Figure 3-9 (b)). Only the front part, the LMS value, in the quantitative data of the chromatogram was used to characterize the binder properties. Research has shown that the large molecular size (LMS) of binder had better correlations with asphalt binder properties than other sizes (Al-Abdul Wahhab et al 1999; Kim and Burati 1993; Kim et al. 2006).

Mixture Performance Analysis

Indirect tensile strength (ITS) properties were mainly measured to evaluate the moisture sensitivity of the mixtures. ASTM D 6931 was used for measuring ITS value and SC-T-70 (SC DOT specification) was used for the moisture sensitivity test procedure. The samples were fabricated at 150 mm diameter having a height of 95 mm and an air void content of 7±1%. The samples were then divided into two groups;

unconditioned (dry) and conditioned (wet). The dry group samples were tested at 25°C with no special conditioning while the wet group samples were tested after conditioning. The wet samples were conditioned by:

- Saturation with vacuum at levels of 55 ~ 80%,
- Immersion under high temperature water bath (60^{o}C) for 24 hours, and
- Temperature adjustment before the test under ambient water bath (25°C)

The ITS and tensile strength ratio (TSR) values were then calculated, and the results were reported as the average.

The Asphalt Pavement Analyzer (APA) was used to evaluate the rutting property of each mixture (as per AASHTO TP 63). The cylindrical samples were fabricated at 150 mm diameter having a height of 75 mm and an air void content of 4±0.5%. Six samples in three molds were then inserted into the analyzer and cured for 6 hours at 64°C for each test. The test was performed under several setting environments; including test temperature (64°C), rubber hose pressure (690 kPa), steel wheel load (445 N), and cycles (8,000). A testing time of 135 minutes is typically needed to complete the rutting evaluation. The rut depths in 2 points of each sample were measured manually with a dial gage and the average of total 12 rut depths was reported for the test set.

The resilient modulus test was performed at temperatures of 5, 25, and 40°C according to ASTM 4123. Four replicated samples were made for each process. Sample dimensions were 150 mm diameter, 95 mm thickness, and 4±0.5% air voids. One of the four samples was used to measure the ITS value by which the repeated load is determined. For the repeated load, 30%, 15% and 5% of the ITS value was used for the

tests at 5, 25, and 40°C, respectively. The load was applied for 0.1 seconds along with a rest period (no loading) of 0.9 seconds and the deformation responses (vertical and horizontal) of 30 loading cycles were measured by linear variable differential transducers (LVDTs). The last 4 (26^{th} to 30^{th}) of the 30 responses were selected to calculate the resilient modulus and the resilient modulus values were then reported as an average of three samples.

The mixture samples were artificially long-term aged using an accelerated aging process (an oven aging for 2 days at 100°C) in the laboratory. This aging method is reported to simulate the pavement aging after 10~20 years of service in the field (Kliewer et al. 1995). The ITS tests were then carried out to investigate the aged stiffness (i.e., cracking potential). One set of three samples for each mixture was tested at 25°C in dry condition.

CHAPTER FOUR

STATISTICAL ANLYSIS METHODS

Statistical analysis methods presented in this study were the combination of logic and arithmetic that can interpret information gathered from chapter 5. The Statistical Analysis System (SAS) (SAS/STAT system version 9.1) and Microsoft Excel software package were used to analyze and evaluate the data. The SigmaPlot software (version 11.0) was also used to express the statistics (e.g., error amount in each individual graph).

A majority of the statistical technique was analysis of variance (ANOVA) since it is an extremely important method in exploratory and confirmatory data analysis (Gelman 2004). ANOVA was performed to determine whether significant differences among sample means existed. In the analyses of this study, the level of significance (α) was selected to be 0.05 (i.e., a confidence level of 95%). Upon determining that there were differences among sample means using the ANOVA, the *F* test along with a randomized complete block design (RCBD) was carried out. Depending on the test results, Fisher's Least Significant Difference (LSD) was also calculated. The detailed ANOVA procedures are described through the following three steps.

The first step was to create RCBD with determining its input variables. WMA additives (Aspha-min, and Sasobit) and control without the additives were considered as a primary treatment (denoted as t) due to its principal attention and other variables (binder sources, aggregate sources, oxidative aging conditions, and compaction conditions) were considered as a secondary treatment or block (denoted as b) as shown in Table 4-1. In the RCBD, the experimental units are first grouped into homogeneous

groups called *blocks*, and the treatments are then assigned at random with the blocks. It is called *complete* because block receives all of the treatments. Effectively, this design strategy can improve the accuracy of the comparisons between treatments by reducing the variability among the experimental units (Kuehl 1999).

Table 4-1: Data for a randomized complete block deign

	Block				
Treatment	1	2	-	*b*	Mean
1	y_{21}	y_{21}	-	y_{1b}	$\bar{y}_{1.}$
2	y_{21}	y_{22}	-	y_{2b}	$\bar{y}_{2.}$
-		–	-	-	-
t	y_{t1}	y_{t2}	-	y_{tb}	$\bar{y}_{t.}$
Mean	$\bar{y}_{.1}$	$\bar{y}_{.2}$	-	$\bar{y}_{.b}$	$\bar{y}_{..}$

The linear model for the RCBD is:

$$y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij}$$

Where, y_{ij} is the observation in *j*-th block receiving treatment *i*

μ is the overall mean

α_i is the effect due to treatment *i*

β_j is the effect due to block *j*

ε_{ij} is the random error associated the response from an experimental unit in block *j* receiving treatment *i*

The second step was to create the ANOVA table for the RCBD as shown in Table 4-2. The ANOVA tests the null hypothesis (H_0) assuming that all the sample means are equal, with a confidence level of 95%. If the F value (ratio) obtained from the table is greater than the F_{crit} value, (which depends on the level of significance and the degree of freedom), H_0 is rejected, meaning that the sample means between different blocks or treatments are not equal.

Table 4-2: ANOVA table for a randomized complete block deign

Source	SS	df	MS	*F*
Treatments	SST	t-1	MST = SST / (t-1)	MST/MSE
Blocks	SSB	b-1	MSB = SSB / (b-1)	MSB/MSE
Error	SSE	(b-1)(t-1)	MSE = SSE / (b-1)(t-1)	
Total	TSS	bt-1		

Note: SS = Sum of squares, df = Degrees of freedom, MS = Mean Square,
SST = Between-treatment sum of squares
SSB = Between-block sum of squares
SSE = Sum of squares for error

The last step was to determine LSD using equation 4-1 if null hypothesis has been rejected from the second step. The LSD is defined as the observed differences between two sample means necessary to declare the corresponding population means difference. Once the LSD was calculated, all pairs of sample means within different treatments and between blocks were compared. If the difference between two sample means was greater than or equal to the LSD, the population means were declared to be statistically different (Ott 2001).

$$LSD_{ij} = t_{\alpha/2}\sqrt{s_w^2\left(\frac{1}{n_i}+\frac{1}{n_j}\right)} \qquad \text{Eq. (4-1)}$$

Where,

n_i and n_j are the respective sample sizes from population i and j

α is the level of significance (0.05 used in this research)

t is the critical t value for $\alpha/2$

s_w^2 is the mean square within samples

CHAPTER FIVE

RESULTS AND DISCUSSIONS

This chapter presents the experimental results obtained in this study. Firstly, in the binder analysis section, the effect of WMA additives on the SBS modified binder performances using Superpave standard methods is discussed. The performance parameters included viscosity, rutting (high failure temperature), fatigue and thermal cracking. The surface topography obtained from AFM is also discussed as the addition of WMA additives in SBS modified binders in this section. Secondly, the OAC results of each SBS modified asphalt mixture and the results of compaction condition study are discussed. The majority of the discussion in this section is about the volumetric properties when compaction levels (100 to 25 gyrations) and temperatures (97 to 154°C) are changed with WMA technologies. Thirdly, in the oxidative aging analysis section, the effects of temperature on the aging level of SBS modified asphalt mixtures with WMA technologies are discussed. The binder aging results from the RTFO are also discussed for comparison with those from oven aging. The percent of LMS using HP-GPC is used to compare and discuss those aging levels. Finally, in the mixture performance analysis section, the performance properties of SBS modified asphalt mixtures using WMA technologies are discussed. The properties included the moisture sensitivity (based on TSR), rutting (final rut depth from APA), resilient modulus (from repeated loading at different temperatures), and long-term property (from ITS after long-term oven aging).

Binder Analysis

Viscosity

The viscosity of asphalt binder at high temperatures is used to determine whether the binder can be handled and pumped at the refinery, terminal, or asphalt plant facility (Asphalt Institute 2003). The lower the viscosity at high temperatures means the more fluid (or softer), indicating that the binder can be easily managed and be coated to the aggregates with less heat applications (i.e., better workability and fuel efficiency). Figure 5-1 shows the variation in viscosity at 135°C for the SBS modified binders based on the WMA additive. A general trend was observed from the results that the addition of Sasobit decreased the SBS modified binder's viscosity, compared to the control SBS modified binder, and this finding was consistent for all binder sources. However, the addition of Aspha-min resulted in increasing the viscosity, and this result is considered to be caused by the addition of fine powder to the binder, which acts as a filler (Akisetty et al. 2008). Aspha-min utilizes short-term foaming action which is active during the mixing and compaction process only. Once all the foaming action has been completed, Aspha-min is more or less extra filler. After the foaming action, Aspha-min particles remain undissolved in the SBS modified binder, therefore increasing the viscosity. In addition, all the binders satisfied the maximum limit for viscosity of asphalt binders at 135°C set forth by Superpave (i.e., 3.0 Pa-s).

The statistical significance of the change in the viscosity as a function of WMA additive and binder source was examined and the results are shown in Table 5-1. In general, the data indicated that the binder source has a significant effect on the viscosity.

In most cases (except for binder source I: Control vs. Aspha-min), the results showed that, within each binder source, the binders have a significant difference in the viscosity depending on the WMA additive.

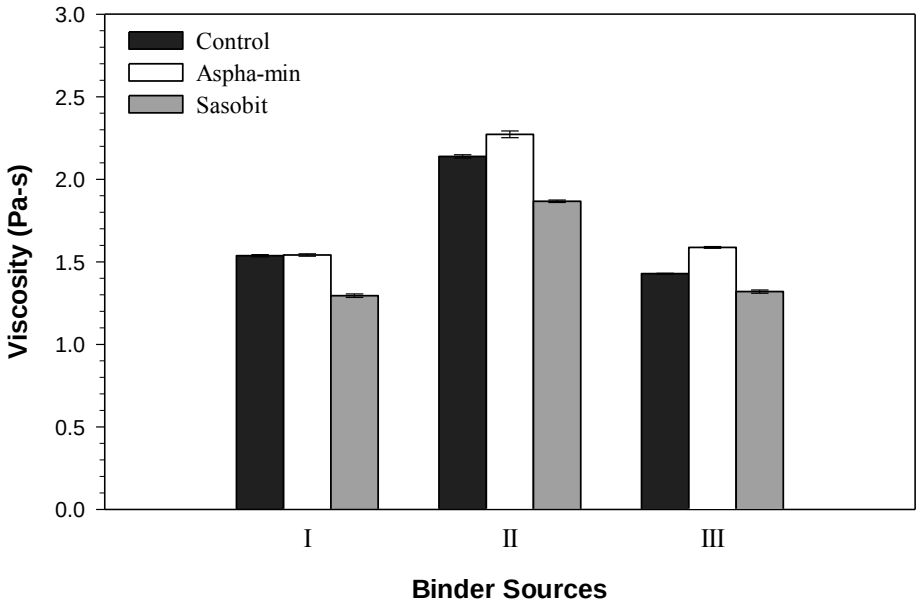


Figure 5-1: Viscosity at 135°C of SBS modified binders based on WMA additive

Table 5-1: Statistical analysis results of the viscosity at 135°C of SBS modified binders as a function of WMA additive and binder source (α=0.05).

Viscosity (135 °C)		Binder I			Binder II			Binder III		
		1	2	3	1	2	3	1	2	3
Binder I	1	-	N	S	S	S	S	S	S	S
	2		-	S	S	S	S	S	S	S
	3			-	S	S	S	S	S	N
Binder II	1				-	S	S	S	S	S
	2					-	S	S	S	S
	3						-	S	S	S
Binder III	1							-	S	S
	2								-	S
	3									-

Note: 1: Control, 2: Aspha-min, 3: Sasobit
N: non-significant, S: significant

Rutting Property

A high failure temperature of the binder grade determination test can be represented as a rutting property. A higher failure temperature means lesser rutting potential in asphalt pavements (Asphalt Institute 2003). The high failure temperature of the SBS modified binders depending on the WMA additive and the binder source in original state (i.e. without aging) and after RTFO aging was measured using the DSR and the results are shown in Figures 5-2 and 5-3. In general, the SBS modified binders containing the additives resulted in the higher failure temperature than the control SBS modified binders regardless of the aging state, suggesting that the addition of Aspha-min or Sasobit has a positive effect on rutting resistance of SBS modified binders. When

Aspha-min is added into SBS modified binders the zeolite particles are thought to act as fillers in SBS modified binders, thereby increasing the stiffness of the binders. The increase in the rutting resistance of the SBS modified binders containing Sasobit is considered to be attributed to the presence of wax crystals in the binders, which causes an increase in the complex modulus of the binders (Edwards and Redelius 2003; Edwards et al. 2006).

The statistical results of the change in the high failure temperature are shown in Table 5-2. For binder sources I and II, the differences between the control binder and the binder containing Sasobit were statistically insignificant within each binder source. Also, the WMA additives were found to have a different effect on the high failure temperature of the SBS modified binders depending on the binder source.

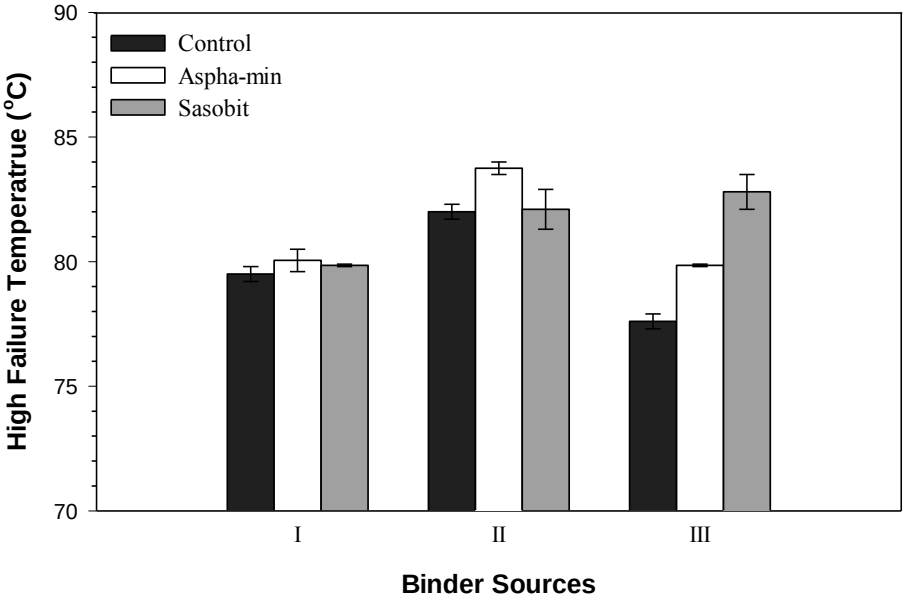


Figure 5-2: High failure temperatures of SBS modified binders based on WMA additive (No aging)

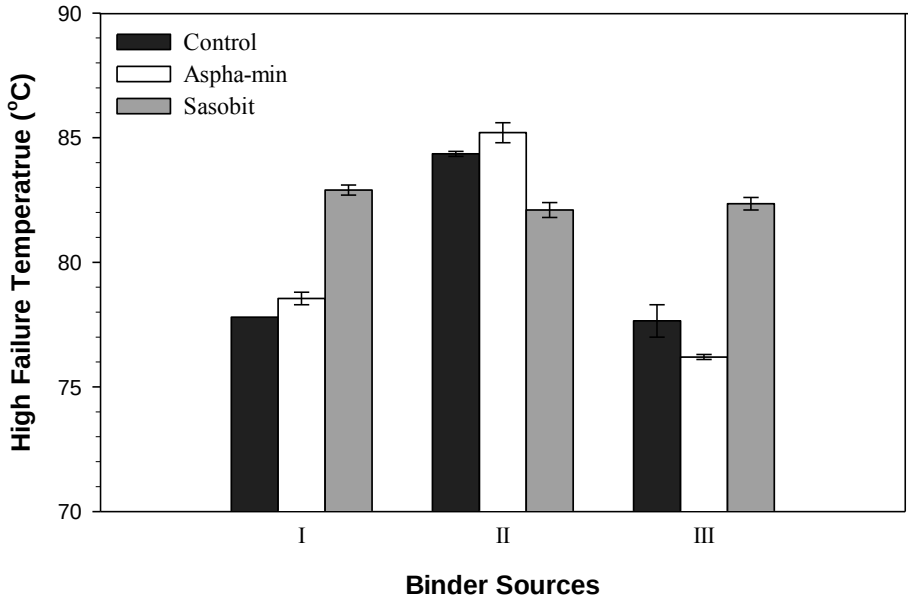


Figure 5-3: High failure temperature of SBS modified binders based on WMA additive (RTFO residual)

Table 5-2: Statistical analysis results of the high failure temperature of SBS modified binders (no aging) as a function of WMA additive and binder source (α=0.05).

High failure temperature		Binder I			Binder II			Binder III		
		1	2	3	1	2	3	1	2	3
Binder I	1	-	N	N	S	S	S	S	N	S
	2		-	N	S	S	S	S	N	S
	3			-	S	S	S	S	N	S
Binder II	1				-	S	N	S	S	N
	2					-	S	S	S	N
	3						-	S	S	N
Binder III	1							-	S	S
	2								-	S
	3									-

Fatigue Cracking Property

The values of ($G^* \times \sin\delta$) from the DSR are used to identify a fatigue cracking characteristic; where, G^* represents stiffness and δ is a viscous or elastic indicator. The lower values are desirable for the resistance to fatigue cracking. PAV aged binders are tested because the asphalt binder becomes stiffer and thus more susceptible to fatigue cracking during its service life (Roberts et al. 1996). The $G^*\sin\delta$ values of each binder (PAV residual) were measured using the DSR at 25°C and the results are illustrated in Figure 5-4. In most of cases, the WMA additives increased the $G^*\sin\delta$ values except the SBS modified binders with Sasobit (from binder source I), indicating that the SBS modified binders containing Aspha-min and Sasobit have possible lower resistance on fatigue cracking than the SBS modified binder without the additives.

The statistical significance of the change in the $G^*\sin\delta$ values are shown in Table 5-3. It was observed that the binder source had a significant effect on the fatigue cracking factor, as expected, while the SBS modified binders with Aspha-min and Sasobit had no significant difference (for two binder sources of I and II), when compared within each binder source.

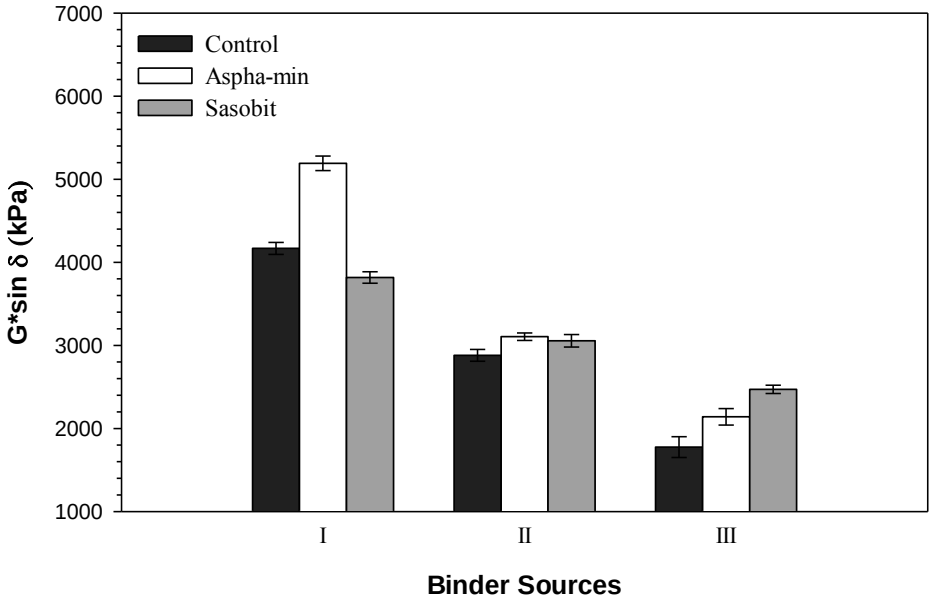


Figure 5-4: G*sin δ at 25°C of SBS modified binders based on WMA additive (PAV residual)

Table 5-3: Statistical analysis results of the G*sin δ at 25°C of SBS modified binders as a function of WMA additive and binder source (α=0.05).

G*sin δ (25°C)		Binder I			Binder II			Binder III		
		1	2	3	1	2	3	1	2	3
Binder I	1	-	S	S	S	S	S	S	S	S
	2		-	N	S	S	S	S	S	S
	3			-	S	S	S	S	S	S
Binder II	1				-	N	N	S	S	S
	2					-	N	S	S	S
	3						-	S	S	S
Binder III	1							-	S	S
	2								-	S
	3									-

Thermal Cracking Property

The BBR is used to determine the binder's propensity to thermal cracking at low temperatures. Two parameters (i.e., creep stiffness and *m*-value) are considered for this property. The creep stiffness is the resistance of the asphalt binder to creep loading and the *m*-value is the change in the creep stiffness with time during loading. A maximum creep stiffness of 300 MPa and a minimum *m*-value of 0.300 are required by Superpave binder specification (Asphalt Institute 2003; Roberts et al. 1996). From the BBR tests at -12°C, the creep stiffness and the *m*-value of each binder (PAV residual) were calculated, and the results are shown in Figures 5-5 and 5-6. The creep stiffness of all binders was much less than 300 MPa, the maximum value for Superpave binder (Figure 6). Similar to the G*sin δ values at 25°C, the creep stiffness values of control SBS modified binders were found to be lowest for all binder sources. With respect to *m*-value, the SBS modified binders containing Sasobit resulted in the lowest m-value properties irrespective of the binder source, indicating that the addition of Sasobit to the SBS modified binders may make the binder less resistant to low temperature cracking. This finding is thought to be associated with the wax crystallization, which usually increases the resistance of plastic deformation of asphalt binders (Edwards et al. 2006). In addition, the SBS modified binders with Aspha-min were generally observed to have slightly higher m-values.

Table 5-4 shows the statistical results of the change in the creep stiffness depending on the additive and binder source. For the binder sources of I and II, Aspha-min and Sasobit were found to have no significantly different influences on the SBS

modified binders in terms of creep stiffness within each binder source. Also, it was evident that the creep stiffness changed between the control binder and the binder containing the WMA additives was statistically significant regardless of the binder source.

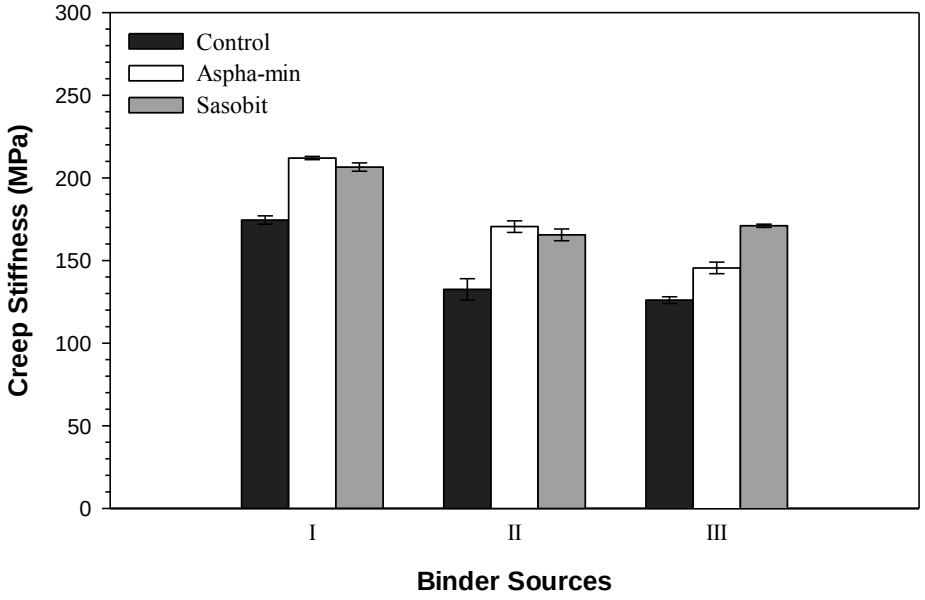


Figure 5-5: Stiffness at -12°C of SBS modified binders based on WMA additive (PAV residual)

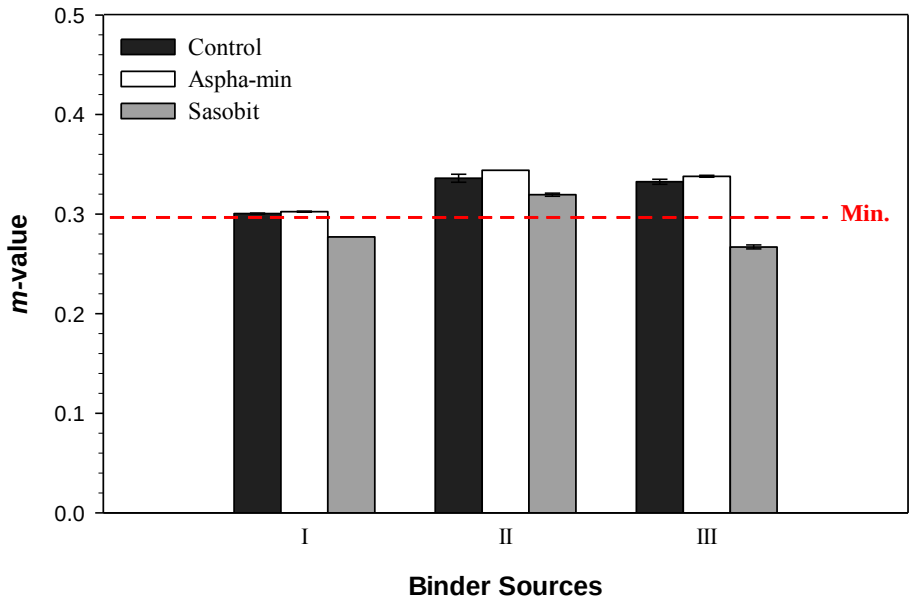


Figure 5-6: *m*-value at -12°C of SBS modified binders based on WMA additive (PAV residual)

Table 5-4: Statistical analysis results of the creep stiffness at -12°C of SBS modified binders as a function of WMA additive and binder source (α=0.05).

Creep stiffness (-12°C)		Binder I			Binder II			Binder III		
		1	2	3	1	2	3	1	2	3
Binder I	1	-	S	S	S	S	S	S	S	N
	2		-	N	N	S	S	S	S	S
	3			-	N	S	S	S	S	S
Binder II	1				-	S	S	N	S	N
	2					-	N	S	S	N
	3						-	S	S	S
Binder III	1							-	S	S
	2								-	S
	3									-

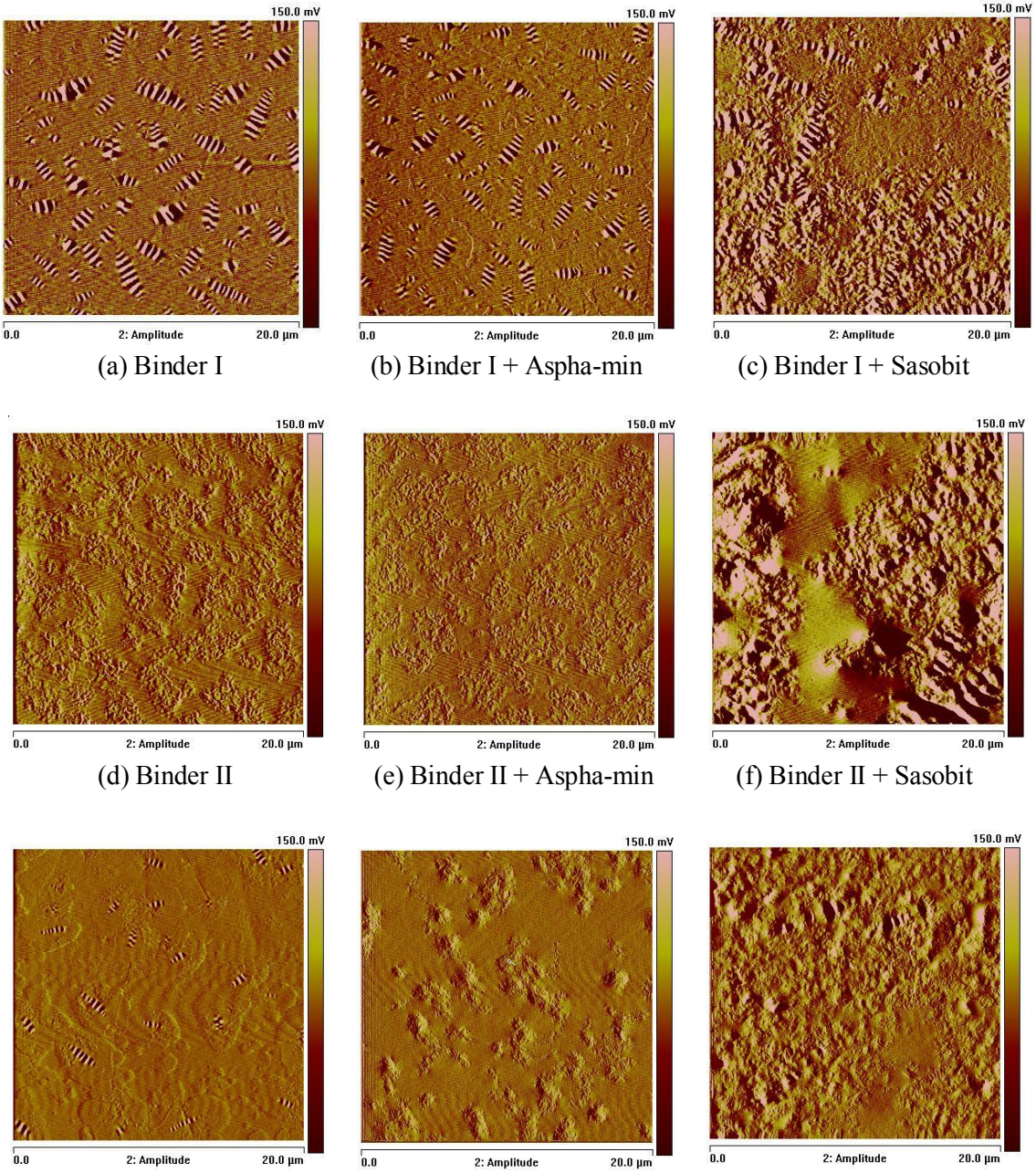
AFM Topography

Three image modes (i.e., height, amplitude, and phase) were produced from AFM. In the two dimensional images (20 × 20 μm), the amplitude mode was used because it represents the highest resolution and presents the clearest topographical picture (Figure 5-7). In the three dimensional images (20 × 20 μm × 50 nm), the height mode was used to produce the same effect (Figure 5-8). The hills and valleys of the surface of the sample are represented by the color scheme bar to the right of each image; brighter colors signify the higher surface portions whilst darker colors represent surface depressions. The first observation that can be made is that the different binder sources each have different unique surface contours before the addition of WMA additives. In Figure 5-7, Binder I and Binder III show very well defined bee like structures scattered across the surface. Binder I shows a more densely packed and higher quantity of bee like structures than Binder III. This particular binder surface structure has an origin that is still a subject of debate. Several researchers (Hefer and Little in 2005; Jager et al. 2004; Loeber et al. 1996) stated that this phenomenon may be due to associations of asphaltenes while Masson et al. in 2006 stated that the bee like structures have a good correlation to the metal content (vanadium and nickel) in asphalt binder and that it has a poor correlation with asphaltenes. Binder II has a wool like surface with a predominant absence of bee like structures; a structure which has not been defined with research to date. Figure 5-8, the three dimensional images, gives a better view of the heights of the rises present on the sample surface. The heights and density of the peaks in the samples (Binder I and III) and the lack thereof in Binder II, correspond with the structures in the

two dimensional images. It is believed that the topography of the different binder sources is related to their atomic or molecular structure. This may have a differing influence on the SBS modified binder properties (i.e., viscosity, rutting resistance etc.).

Aspha-min binder combinations are shown to have the effect of reducing the peaks and creating depressions on the sample surface. This is more clearly seen on the Nano scale (Figure 5-8) than the micro (Figure 5-7). Clearly observed in Figure 5-7, Binder I containing Aspha-min shows surface indents throughout the image and Binder III containing Aspha-min exhibits a more undulating surface. Binder II with Aspha-min, although not easily distinguishable, shows a smoother surface. It is hypothesized that the water molecules from Aspha-min caused the peak reduction or the change in the surface.

As seen in the Figures, Sasobit binder combinations are shown to have the effect of creating rugged, interconnected peaks with harsh looking surface space as. All binders containing Sasobit show higher and densely linked peaks than those with Aspha-min and the control samples. In particular, Binder II containing Sasobit shows more rounded summits and Binder III containing Sasobit exhibits sharper peaks than the others (Figure 5-8). It is hypothesized that the Sasobit alters the surface structure of the binder through its re-crystallization after cooling. Overall, WMA additives have a definite impact of the topography of the SBS modified asphalt used and its impact also may diversely manipulate the binder properties (i.e., viscosity, rutting resistance etc.).

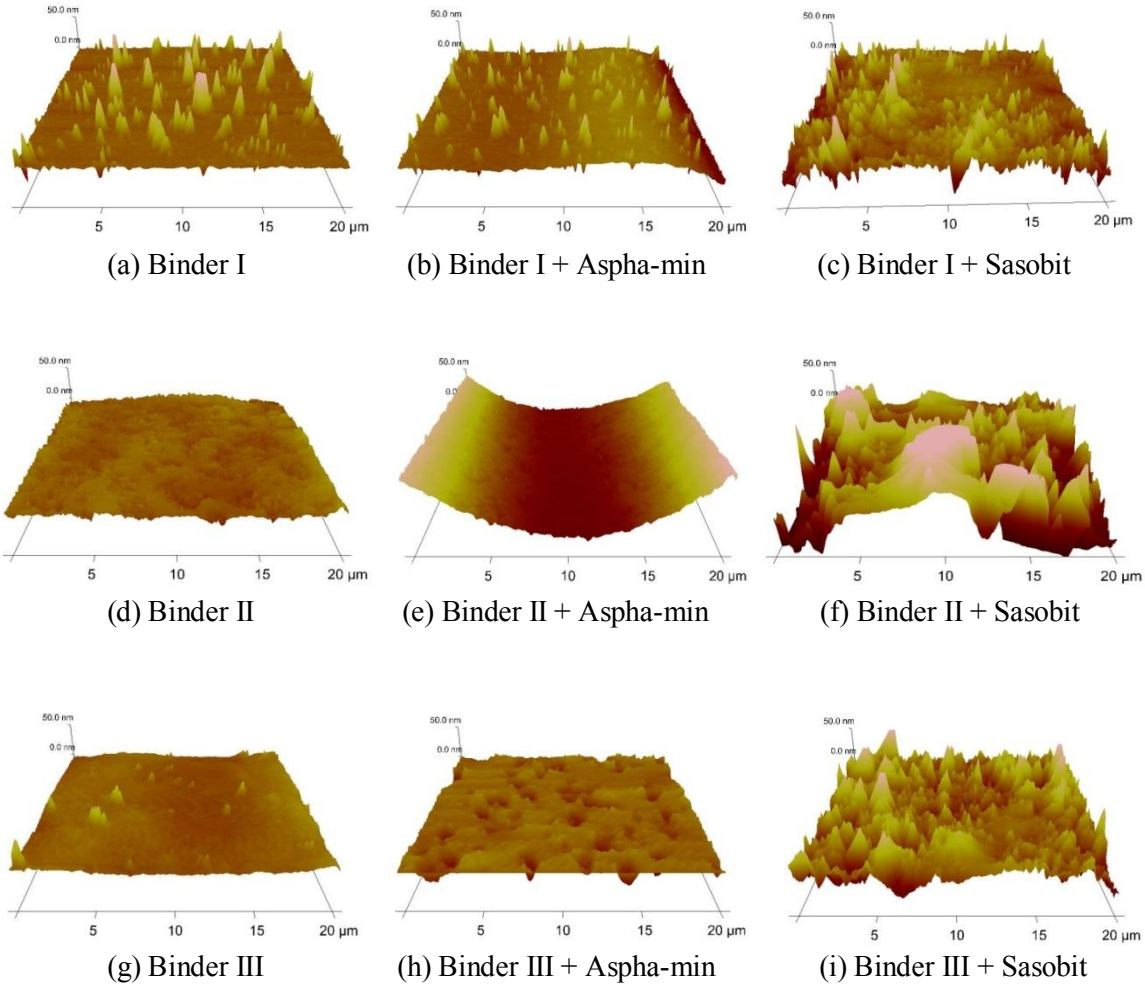


(a) Binder I (b) Binder I + Aspha-min (c) Binder I + Sasobit

(d) Binder II (e) Binder II + Aspha-min (f) Binder II + Sasobit

(g) Binder III (h) Binder III + Aspha-min (i) Binder III + Sasobit

Figure 5-7: AFM 2D images of SBS modified binders based on WMA additive



(a) Binder I (b) Binder I + Aspha-min (c) Binder I + Sasobit

(d) Binder II (e) Binder II + Aspha-min (f) Binder II + Sasobit

(g) Binder III (h) Binder III + Aspha-min (i) Binder III + Sasobit

Figure 5-8: AFM 3D images of SBS modified binders based on WMA additive

Mix Design and Compaction Condition Study

Superpave Mix Design

The Superpave mix design procedure was used to determine the optimum asphalt contents (OAC) of each SBS asphalt mixture. Table 5-5 summarizes the OAC, maximum specific gravity (MSG), bulk specific gravity (BSG), and other related data of the mix designs. The mixes made with aggregate A were found to have approximately 0.7~1.5 %

higher OAC than those with aggregate B. It is believed that granite aggregate (type A) has higher absorption capacity (0.4% more) and rougher surface texture than marble schist aggregate (type B) so that more binder could be absorbed. This tendency has also been similar in other research projects in the laboratory irrespective of binder types (i.e., source, polymer modification, and RAP). In addition, the binder source showed the variability of the OAC value in each aggregate source (i.e., binder I was lower in aggregate A while higher in B). However, the difference was not significant in each aggregate source. The mix design results were also used for SBS asphalt mixes' incorporation with WMA technologies for compaction condition study and mixture performance analysis.

Table 5-5: Superpave mix design results for SBS modified asphalt mixtures

Properties	Aggregate A		Aggregate B	
	Binder I	Binder II	Binder I	Binder II
OAC (%)	4.8	5.1	4.1	3.6
MSG	2.537	2.536	2.618	2.627
BSG	2.434	2.431	2.517	2.522
Air void (%)	4.0	4.0	4.0	4.0
VMA (%)	15.34	16.14	13.85	12.76
VFA (%)	73.67	74.29	72.04	68.82

Note: OAC, optimum asphalt content; MSG, maximum specific gravity; BSG, bulk specific gravity.

Volumetric Properties as a Function of Compaction Level

Figure 5-9 (a) shows the air void contents of the SBS modified mixtures as a function of the compaction level. One can make the general observation that the air void contents decreased, as expected, as the compaction levels increased, from 25 to 100 gyrations. Additionally it can be seen that, for mixtures using aggregate source A and B, the air voids for the mixtures ranged from 7±1% and 4±1% using 25 and 100 gyrations, respectively. At all the studied compaction levels shown, the air voids for the mixtures using aggregate B was found to be lower when compared with those mixtures with aggregate A.

At 100 gyrations, the average air void for mixtures with aggregate A was found to be 4.0%, 4.3%, and 4.8% for the control mixtures, and those with Aspha-min and Sasobit, respectively. From this analysis, it was seen that for the aggregate source A, the air voids for the WMA mixtures were found to be higher than HMA (control) mixtures. However for mixtures with aggregate B, the average air voids at 100 gyrations were found to be 3.5%, 3.4%, and 3.3% for the control mixtures, and those with Aspha-min and Sasobit, respectively. The aggregate source B results indicated that WMA mixtures showed lower or similar air voids when compared to control mixtures. The test results showed that the air voids of the mixtures behaved differently with aggregate type and structure. From this limited study, one can note that aggregate structure may play an important role in the distribution of air voids for the control and WMA mixtures. Furthermore, all mixtures satisfied the targeted air void range of 4±1% at N_{design} = 100 gyrations while still compacting at lower temperatures.

At 25 gyrations, the average air void for mixtures with aggregate A was found to be 7.9%, 7.2% and 8.1% for the control mixtures, and those with Aspha-min and Sasobit, respectively. Similar to air voids at N_{design} = 100 gyrations, it was observed that at 25 gyrations for aggregate source A, the air voids for the WMA mixtures were found to be similar or lower than control mixtures. However for mixtures with aggregate B, the average air voids at 25 gyrations were found to be 6.8%, 6.5%, and 6.3% for the control mixtures and those with Aspha-min and Sasobit, respectively. The aggregate source B results indicated that WMA mixtures showed lower air voids when compared to control mixtures. The test results indicated WMA mixtures behaved differently at 100 and 25 gyrations with respect to the air void contents for the aggregate sources A and B, thereby indicating that the air voids are mainly dependent on the aggregate type and structure for WMA mixtures. Furthermore, all mixtures satisfied the targeted air void range of 7±1% at 25 gyrations and WMA mixtures resulted in better compaction at initial level (25 gyrations) of compaction and at lower temperatures (135°C).

Table 5-6 shows the statistical importance of the change in the air void contents with increasing compaction levels. In general, the air void contents of each mixture were affected significantly by the four different compaction levels used in this study. From the table it was observed that at 100 gyrations, for aggregate source A, the air void contents were found to be insignificant for mixtures in the combinations used between control-Aspha-min and Sasobit-Aspha-min, respectively. Whereas the air voids were found to be significant for the combination between control-Sasobit. For the aggregate source B, the air voids were found to be insignificant for all the combinations utilized.

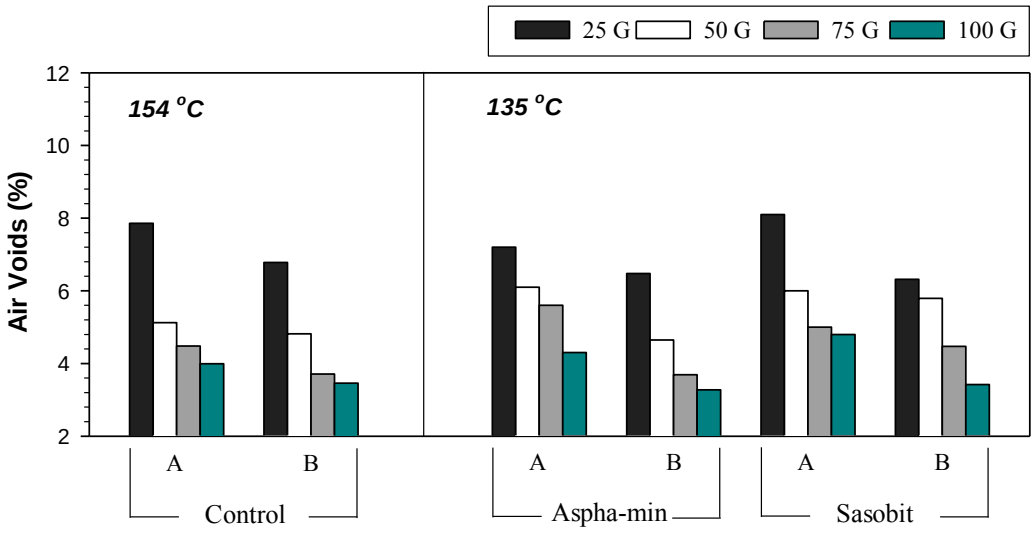
From Table 5-6, it was observed that at 25 gyrations, for aggregate source A, the air void contents were found to be insignificant for mixtures of combinations between control-Aspha-min and control-Sasobit, while significant difference was observed between Sasobit-Aspha-min, respectively. For the aggregate source B, the air voids were found to be insignificant for all the combinations studied. In general for both sources of aggregate, the air void contents for WMA mixtures between 50 and 75 gyrations were found to be significant when compared to the control mixtures. One can perhaps notice that the air void contents of the mixtures are influenced by the compaction levels, WMA additives, and aggregate types.

Figure 5-9 (b) shows that the bulk density values increased with an increase in the compaction levels. Bulk densities for the mixtures with aggregate B were found to be higher when compared to mixtures with aggregate A, as the unit weight of aggregate B is higher than that of aggregate A, as shown in the Table 3-3. It was observed that in most cases, the bulk densities were found to be insignificant at the respective 25 and 100 gyrations. However, in only two cases (control-Sasobit and control-Aspha-min) at 100 gyrations, significant differences in the bulk densities were observed between aggregates A and B.

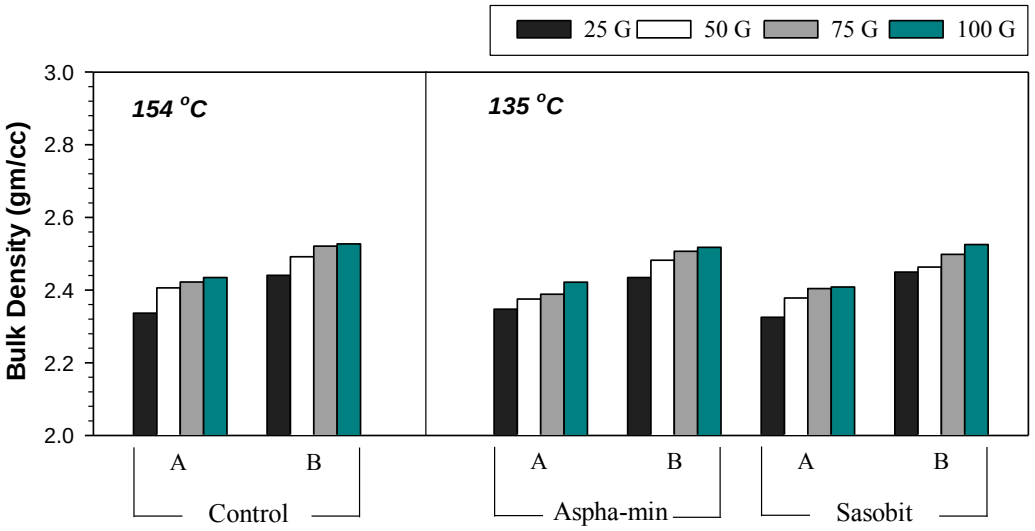
The VMA values, from Figure 5-9 (c), showed the same trends with the air void results; decreasing with an increase in the compaction levels for all the mixtures. For a pavement to have adequate film thickness there must be sufficient space between the aggregate particles in the compacted pavement. This void space is referred to as VMA. It must be sufficient to allow adequate effective asphalt (that which is not absorbed into the

aggregate particles) and air voids (Chadbourn et al. 2000). For the compaction levels of 25 and 100, when comparing aggregate sources, one can see comparable VMA values between the control and the WMA mixtures.

The VFA is the percentage of voids in the compacted aggregate mass that are filled with asphalt binder. The VFA property is an important parameter not only as a measure of relative durability, but also because there is an excellent correlation between it and percent density. If the VFA is too low, there is not enough asphalt to provide durability and if too high it can densify under traffic and bleed. In the present study, the VFA values for all the mixtures as shown in Figure 5-9 (d) increased with a rise in the compaction levels for all mixtures. It was also revealed that there is no significant difference in the VFA values between the control and WMA mixtures studied at varying compaction levels.

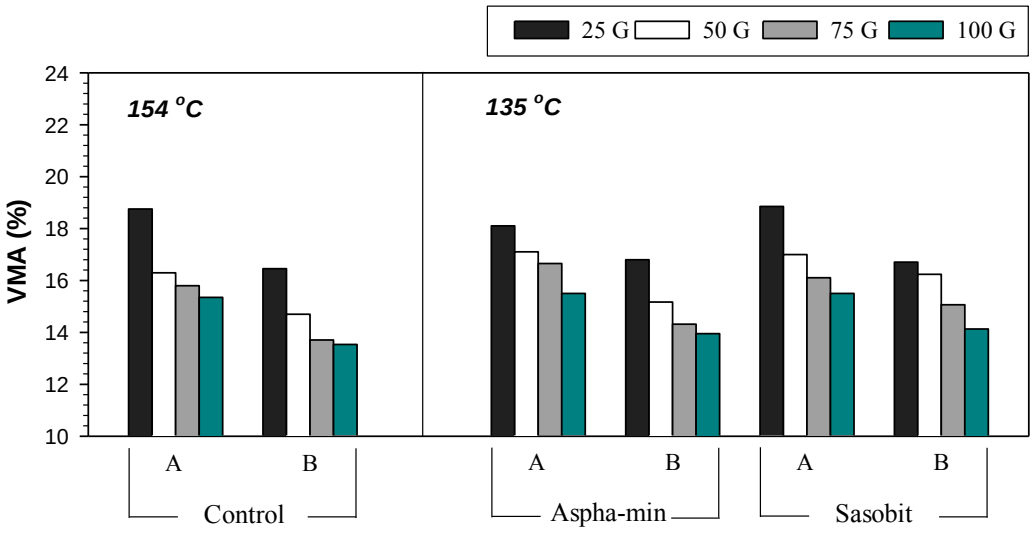


(a)

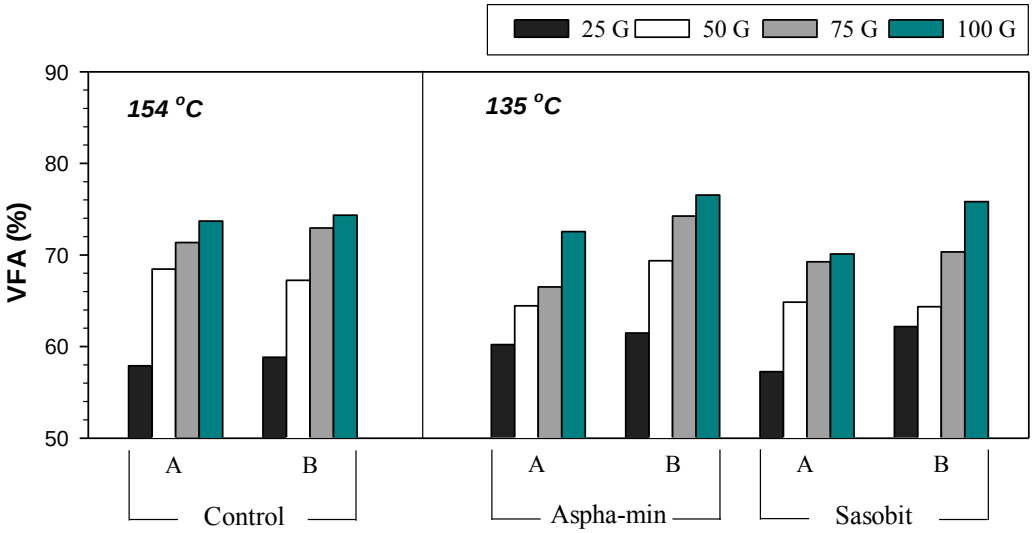


(b)

Figure 5-9: Relationship between volumetric properties of SBS modified asphalt mixtures regarding varying compaction levels



(c)



(d)

Figure 5-9: (Continued)

Table 5-6: Statistical analysis results of air voids (%) of SBS modified asphalt mixtures as a function of WMA additive and compaction level (α=0.05): (a) Aggregate A; (b) Aggregate B.

(a)		Control				Aspha-min				Sasobit			
		25	50	75	100	25	50	75	100	25	50	75	100
Control	25	-	N	S	S	N	S	S	S	N	S	S	S
	50		-	S	S	S	S	S	N	S	N	N	N
	75			-	S	S	S	S	N	S	S	S	S
	100				-	S	S	S	N	S	S	S	S
Aspha-min	25					-	S	S	S	S	S	S	S
	50						-	S	S	N	N	N	S
	75							-	S	S	S	N	N
	100								-	S	S	S	S
Sasobit	25									-	S	S	S
	50										-	N	N
	75											-	N
	100												-

(b)		Control				Aspha-min				Sasobit			
		25	50	75	100	25	50	75	100	25	50	75	100
Control	25	-	S	S	S	N	S	S	S	N	N	S	S
	50		-	S	S	S	S	N	S	N	S	N	S
	75			-	S	S	S	N	N	S	S	S	N
	100				-	S	S	S	S	S	S	S	N
Aspha-min	25					-	S	S	S	N	N	S	S
	50						-	S	S	N	N	S	S
	75							-	N	S	S	N	S
	100								-	S	S	N	N
Sasobit	25									-	N	S	S
	50										-	S	S
	75											-	N
	100												-

Note: Number of Gyrations (25, 50, 75, and 100)
N: non-significant, S: significant

Volumetric Properties as a Function of Compaction Temperature

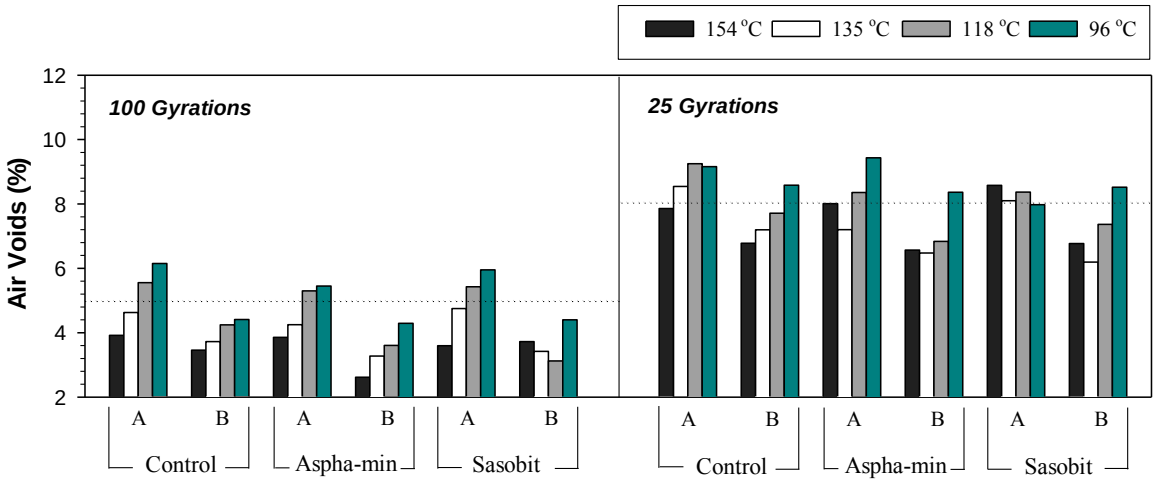
Figure 5-10 (a) shows the air void contents of the SBS modified asphalt mixtures as a function of the compaction temperature. At 100 gyrations, the air voids for all the mixtures with aggregate A satisfied the requirements of 4±1% when compacted at 154 and 135°C, respectively. However, the two compaction temperatures (118 and 96°C) with aggregate A are thought to be inappropriate for N_{design} = 100 gyrations due to air void contents of greater than 5% irrespective of the mixture types. In addition, all mixtures with aggregate B satisfied the targeted air voids (4±1%) throughout all temperature ranges (154 to 96°C), except the mixture made with Aspha-min at 154°C, which showed 2.6% air voids. However, the higher temperature of 154°C was used for comparison purposes and not generally adopted for WMA technology. At 25 gyrations, WMA mixtures made with both aggregates showed less air voids than control mixtures made with the same aggregates at lower temperatures (135 and 118°C), indicating that WMA additives can ease the compaction effort during the initial stage while working at lower temperatures.

Table 5-7 shows statistical analysis results of the change in the air void contents with four compaction temperatures. No significant differences were relatively observed throughout the table, indicating that compaction temperatures have less influence on air voids when compared with gyration efforts. However, significance differences were observed at lower temperatures (135 to 96°C) for the combination between control - Aspha-min and Aspha-min - Sasobit with aggregate A (at 25 gyrations) and aggregate B (at 100 gyrations), respectively. Aggregate source B especially, showed significant

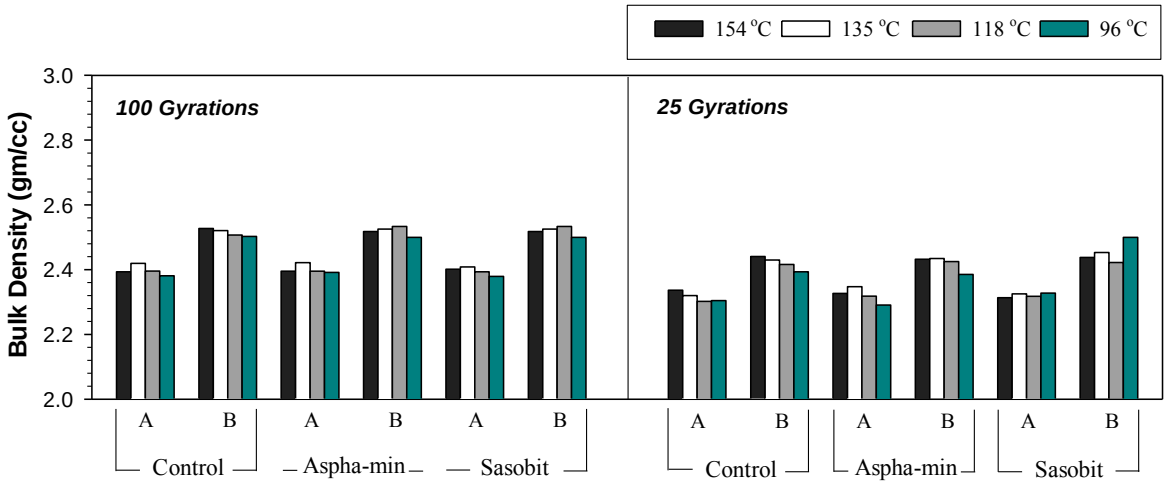
differences at the lower compaction temperature of 96°C for the combinations mentioned above. Based on the statistical results, it was observed that the compaction temperatures are generally not a major parameter for air void content while lower compaction temperatures with WMA additives may have significant change in the air voids.

Figure 5-10 (b) illustrates the relationship between bulk density and compaction temperatures. In general, the bulk density values decreased with the decrease in compaction temperatures and densities for the mixtures with aggregate B were found to be higher when compared to mixtures with Aggregate A. In addition, for both sources of aggregates, while working at lower temperatures, it was observed that WMA mixtures had better or similar densities as compared with the control mixtures.

Figure 5-10 (c and d) illustrates the relationship between VMA and VFA for different compaction temperatures, respectively. As expected, the VMA of all the mixtures increased with the decrease in compaction temperatures. For aggregate A, it was observed that for the compaction temperatures at 118 and 96°C, VMA values for all the mixtures were found to be greater than 16%; indicating that irrespective of HMA/WMA, mixtures showed increased VMA values at lower compaction temperatures. Additionally, for both sources of aggregates, the results indicated that VFA values for all the mixtures studied decreased with the decrease in compaction temperatures. WMA mixtures showed increased VFA values as compared with control mixtures for the studied range of compaction temperatures.

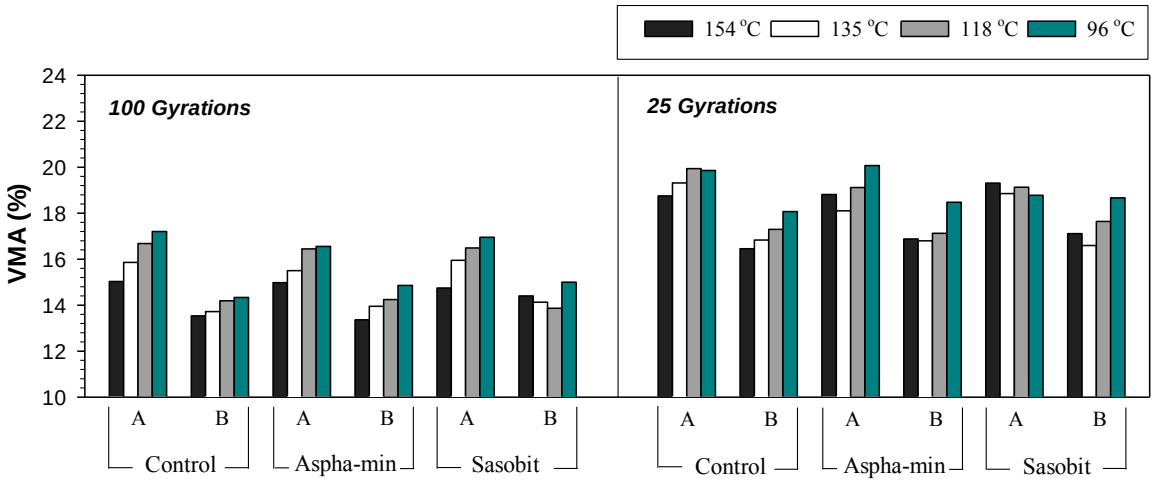


(a)

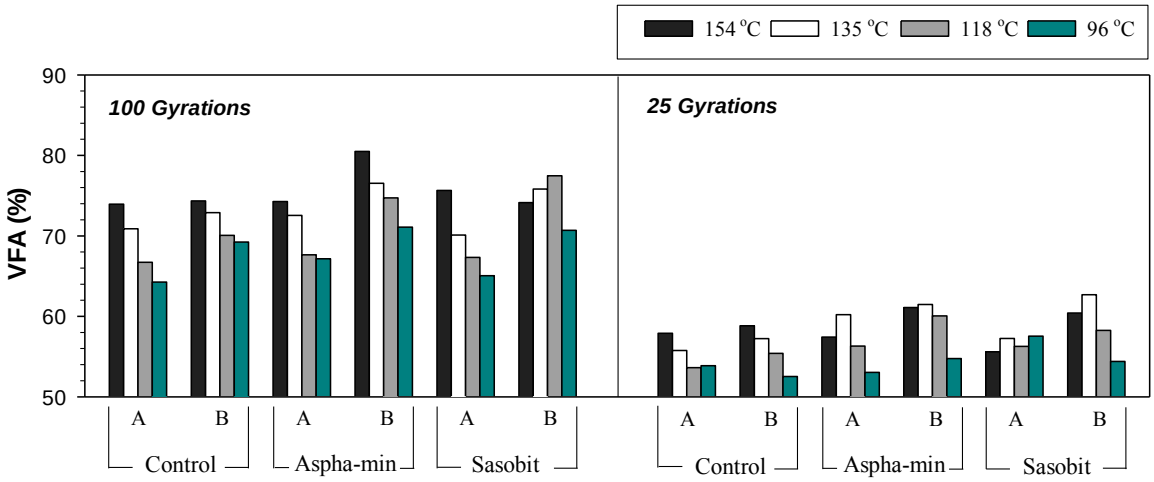


(b)

Figure 5-10: Relationship between volumetric properties of SBS modified asphalt mixtures regarding different compaction temperatures and compaction levels



(c)



(d)

Figure 5-10: (Continued)

Table 5-7: Statistical analysis results of air voids (%) of SBS modified asphalt mixtures as a function of WMA additive and compaction temperature (α=0.05): (a) Aggregate A; (b) Aggregate B.

(a)		Control								Aspha-min								Sasobit							
		154		135		118		96		154		135		118		96		154		135		118		96	
Control	154			**N**	N	**N**	S	**S**	S	**N**	S	**N**	N	**N**	S	**N**	S	**S**	S	**N**	S	**N**	S	**N**	S
	135					**N**	N	**N**	S	**N**	N	**S**	N	**N**	N	**N**	N	**N**	N	**N**	N	**N**	N	**N**	N
	118							**N**	N	**N**	N	**S**	N	**N**	N	**N**	N	**N**	N	**N**	N	**N**	N	**N**	N
	96									**S**	N	**S**	S	**N**	S	**N**	N	**N**	S	**S**	S	**N**	N	**S**	N
Aspha-min	154											**S**	S	**N**	N	**N**	N	**S**	N	**S**	N	**N**	N	**N**	N
	135													**N**	S	**S**	S	**N**	N	**S**	S	**N**	N	**N**	S
	118															**N**	S	**N**	N	**S**	N	**N**	N	**N**	N
	96																	**N**	N	**S**	S	**N**	S	**N**	N
Sasobit	154																			**N**	N	**N**	N	**S**	N
	135																					**N**	N	**N**	S
	118																							**N**	N
	96																								

(b)		Control								Aspha-min								Sasobit							
		154		135		118		96		154		135		118		96		154		135		118		96	
Control	154			**N**	N	**N**	S	**S**	S	**N**	N	**N**	S	**N**	N	**S**	S	**N**	N	**N**	N	**N**	S	**N**	S
	135					**N**	N	**S**	N	**S**	N	**N**	N	**N**	N	**S**	S	**S**	N	**N**	N	**N**	N	**N**	N
	118							**N**	N	**N**	N	**N**	N	**N**	N	**N**	S	**S**	S	**S**	N	**N**	S	**N**	N
	96									**S**	S	**N**	S	**S**	N	**N**	S	**S**	S	**S**	N	**N**	S	**N**	N
Aspha-min	154											**N**	N	**N**	N	**S**	S	**S**	N	**N**	S	**N**	N	**S**	S
	135													**N**	N	**S**	S	**N**	N	**N**	N	**N**	N	**S**	S
	118															**S**	N	**N**	N	**N**	N	**N**	N	**N**	S
	96																	**N**	N	**N**	N	**N**	N	**N**	N
Sasobit	154																			**N**	N	**N**	S	**N**	S
	135																					**N**	N	**S**	N
	118																							**N**	N
	96																								

Note: Compaction temperatures (154, 135, 118, and 96 °C) at **25** /100 gyrations
N: non-significant, S: significant

Oxidative Aging Analysis

Effect of Short-Term Oven Aging

Figure 5-11 depicts the LMS (%) change of SBS modified binders in the mixes depending on WMA additives (Control, Aspha-min, and Sasobit) and binder sources (I, II, and III) after short-term oven aging (STOA) procedures in the laboratory. As expected, the general trend observed was that a higher aging temperature and a longer aging period led to a higher LMS value of the binder, regardless of the additives and the binder sources. When comparing the binder sources, binder source I resulted in higher LMS values than those from source II and III after STOA. This is thought to be attributed to the higher LMS value of the binder at its original condition (Table 3-2).

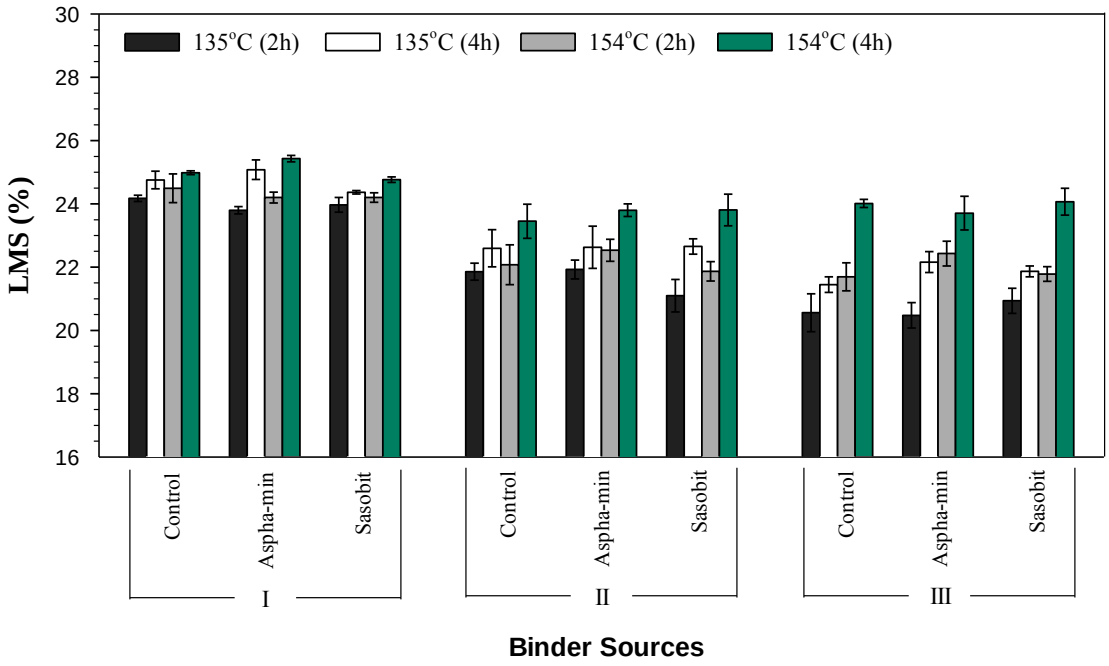


Figure 5-11: LMS (%) change depending on short-term oven aging conditions

To minimize the binder source effect and normalize the test results, the LMS ratio was used for the quantification of short-term oven aging level (LMS ratio = LMS value after aging / LMS value before aging). For binder sources of I, II, and III, the average increase in the LMS ratios as a function of the binder types (Control, Aspha-min, and Sasobit) was found to be 22.4%, 21.8%, and 22.7%, respectively. This result indicates that the WMA additives are not a significant factor to influence the aging level (measured by the LMS ratio) at the same aging temperature and time. However, emphasis must be placed on the fact that the mixes made with the additives are short-term aged at lower temperature than the conventional HMA mixes and the reduced aging temperature seems to make the binders in the mixes less oxidized. When compared between 135°C and 154°C, the lower aging temperature of 135°C for 2 hours resulted in the less increase in the LMS ratios (1.5%, 2.9%, and 7.3% reduction for the binder sources I, II, and III, respectively). With the longer aging time of 4 hours used, the LMS ratios of the binders aged at 135°C were observed to be 1.6%, 5.8%, and 11.8% less than those of the binders at 154°C for the three binder sources of I, II, and III, respectively, suggesting that the benefit of using the warm additives becomes even greater, especially where the longer hauling distance is required.

Table 5-8 shows the statistical significance of the change in the LMS (%) values. In most cases, there was no significant difference at the $\alpha = 0.05$ level among the LMS values of SBS modified binders (control vs. Aspha-min, control vs. Sasobit, and Aspha-min vs. Sasobit) at the same aging conditions, when compared within each binder source. From this result, it was noted that the effect of aging on mixing with hot aggregates was

not significantly different between the two aggregate temperatures of 163°C and 143°C. The result can be explained by relatively short mixing time of 90 seconds, compared to short-term oven aging periods of 2 ~ 4 hours. On the other hand, it is evident that the differences between the STOA conditions have statistically a significant influence on the LMS values of SBS modified binders in the mixes. It suggests that the SBS modified binders with the additives have less aging levels than the control SBS modified binders which is produced and short-term aged at higher temperatures. In addition, the statistical results showed that the LMS values of SBS modified binders aged at the two STOA conditions of 135°C (4h) and 154°C (2h) were not significantly different within each binder source, regardless of the warm additives. This result is consistent with the previous research (Lee et al. 2009), which reported that the commonly used two STOA methods have the same effect on binder aging at the 5% level.

Table 5-8: Statistical analysis results of LMS (%) change of SBS modified binders as a function of short-term oven aging condition and WMA additive: (a) Binder I; (b) Binder II; (c) Binder III.

(a)		Control				Aspha-min				Sasobit			
		1	2	3	4	5	6	7	8	9	10	11	12
Control	1	-	S	N	S	N	S	N	S	N	N	N	S
	2		-	N	N	S	N	S	S	S	N	S	N
	3			-	N	S	S	N	S	N	N	N	N
	4				-	S	N	S	N	S	S	S	N
Aspha-min	5					-	S	N	S	N	S	N	S
	6						-	S	N	S	S	S	N
	7							-	S	N	N	N	S
	8								-	S	S	S	S
Sasobit	9									-	N	N	S
	10										-	N	N
	11											-	S
	12												-

(b)		Control				Aspha-min				Sasobit			
		1	2	3	4	5	6	7	8	9	10	11	12
Control	1	-	N	N	S	N	S	N	S	N	S	N	S
	2		-	N	S	N	N	N	S	S	N	N	S
	3			-	S	N	N	N	S	S	N	N	S
	4				-	S	S	S	N	S	S	S	N
Aspha-min	5					-	N	N	S	S	S	N	S
	6						-	N	S	S	N	N	S
	7							-	S	S	N	N	S
	8								-	S	S	S	N
Sasobit	9									-	S	S	S
	10										-	S	S
	11											-	S
	12												-

(c)		Control				Aspha-min				Sasobit			
		1	2	3	4	5	6	7	8	9	10	11	12
Control	1	-	S	S	S	N	S	S	S	N	S	S	S
	2		-	N	S	S	S	S	S	N	N	N	S
	3			-	S	S	N	S	S	S	N	N	S
	4				-	S	S	S	N	S	S	S	N
Aspha-min	5					-	S	S	S	N	S	S	S
	6						-	N	S	S	N	N	S
	7							-	S	S	N	S	S
	8								-	S	S	S	N
Sasobit	9									-	S	S	S
	10										-	N	S
	11											-	S
	12												-

Note: Short-term oven aging conditions 1*: 135℃ (2h), 2: 135℃ (4h), 3: 154℃ (2h), 4: 154℃ (4h)
N: non-significant, S: significant

Effect of RTFO aging

Figure 5-12 depicts the LMS (%) change of nine SBS modified binders (3 binder sources with Control and 2 WMA additives) before RTFO (no aging) and after two RTFO aging (135 and 165°C at 85 min). One can generally observe that the LMS values increased after the RTFO aging procedure and at the higher temperature of the RTFO irrespective of binder types. The effect of the binder sources resulted in similar trends to the results from the STOA, meaning that both laboratory aging procedures do not notably change the property of the asphalt binders. However, the average LMS value after the RTFO was approximately 2% less than the STOA. One reasonable assumption is that the thinner binder films coated on the aggregates are more severely aged in the oven (STOA) and are more broadly exposed than the binders coated on the bottle and aged by RTFO.

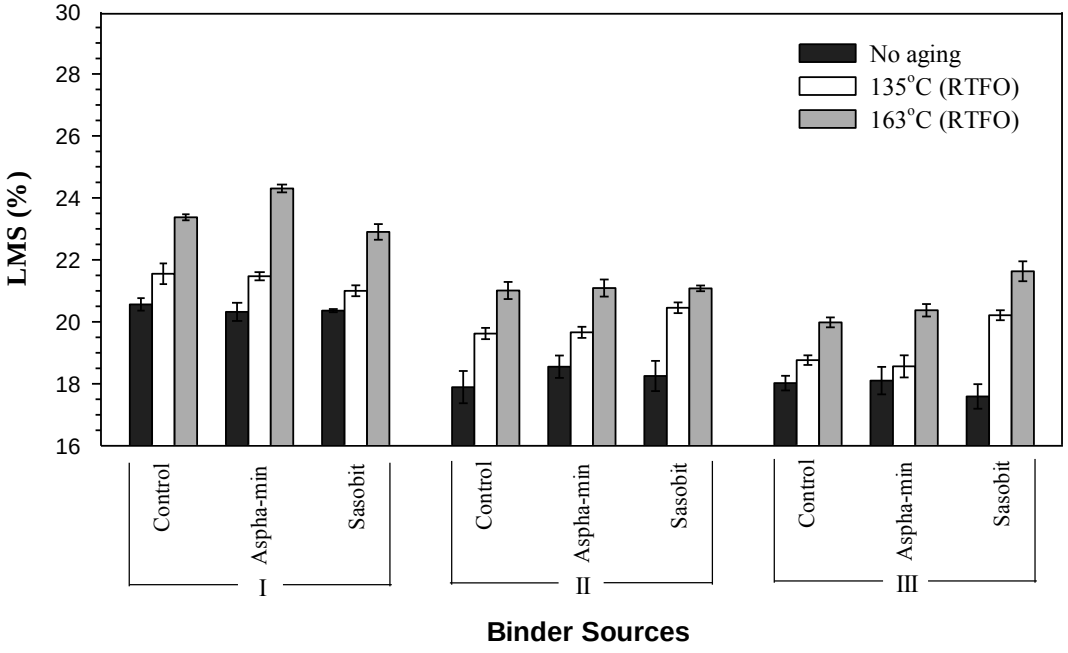


Figure 5-12: LMS (%) change depending on RTFO aging temperatures

The LMS ratio was calculated for the purpose of the quantification of short-term aging level from the RTFO. For the RTFO aging at 135°C, the average increase in the LMS ratios depending on the binder types of Control, Aspha-min, and Sasobit was observed to be 6.2%, 4.7%, and 10%, respectively. When the standard temperature of 163°C was utilized for the RTFO aging, the increase in the LMS ratios was 14.0%, 15.3%, and 17.0% for Control, Aspha-min, and Sasobit, respectively. The results suggest that the control binder and the binder with Aspha-min have similar aging levels after the RTFO aging procedures, when comparing the LMS change. Also, the SBS modified binder with Sasobit showed the highest increase in the LMS ratios at the same aging condition. However, it is not appropriate to conclude that the binder with Sasobit is susceptible to short-term aging by the RTFO, since the additive has the effect of reducing the temperatures significantly.

A reasonable comparison can be made between 135°C for WMA and 163°C for HMA since lower operation temperatures are the ultimate purpose of WMA while higher operation temperature are only for HMA. The average LMS ratio resulted in 9.3% (for Aspha-min) and 4.0% (for Sasobit) reduction in the binders containing WMA additives at 135°C as compared to the control binders at 163°C, suggesting that oxidative aging can be delayed with WMA technologies.

Table 5-9 shows the statistical significance of the change in the LMS value as a function of the WMA additives and the RTFO aging temperatures. In general, the data showed that the aging temperature plays a significant role in the LMS value of the SBS modified binders, regardless of the additives. In other words, the RTFO aging

temperature is considered to be a significant factor in determining the LMS values. Clearly, there can be little doubt that the use of WMA additives is very effective in decreasing the aging level of the binders. Also, the binders with Control and Aspha-min were observed to have an insignificant difference in the aging level (LMS from the GPC test) within the same aging conditions.

Figure 5-13 illustrates the overall aging effect (the increase in the LMS ratios) depending on the short-term aging conditions (RTFO and STOA on the basis of no aged binder as a zero). The figure helps to give the useful information of the comparison among the aging levels used in this studied. As explained through, the aging temperature and time influenced the increase in a binder aging and the STOA resulted in the higher aging levels than the RTFO.

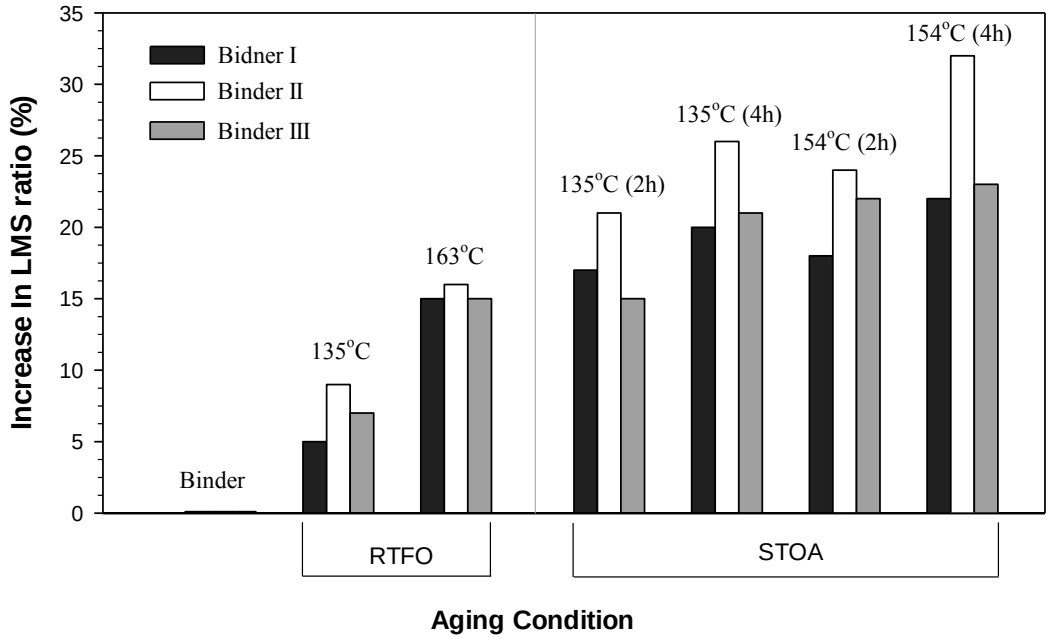


Figure 5-13: Quantification of short-term aging effect (Increase in LMS ratio)

Table 5-9: Statistical analysis results of LMS (%) change of SBS modified binders as a function of RTFO aging condition and WMA additive: (a) Binder I; (b) Binder II; (c) Binder III.

(a)		Control			Aspha-min			Sasobit		
		1	2	3	4	5	6	7	8	9
Control	1	-	S	S	N	S	S	N	S	S
	2		-	S	S	S	S	S	N	S
	3			-	S	S	N	S	S	N
Aspha-min	4				-	S	S	N	S	S
	5					-	S	S	S	S
	6						-	S	S	N
Sasobit	7							-	S	S
	8								-	S
	9									-

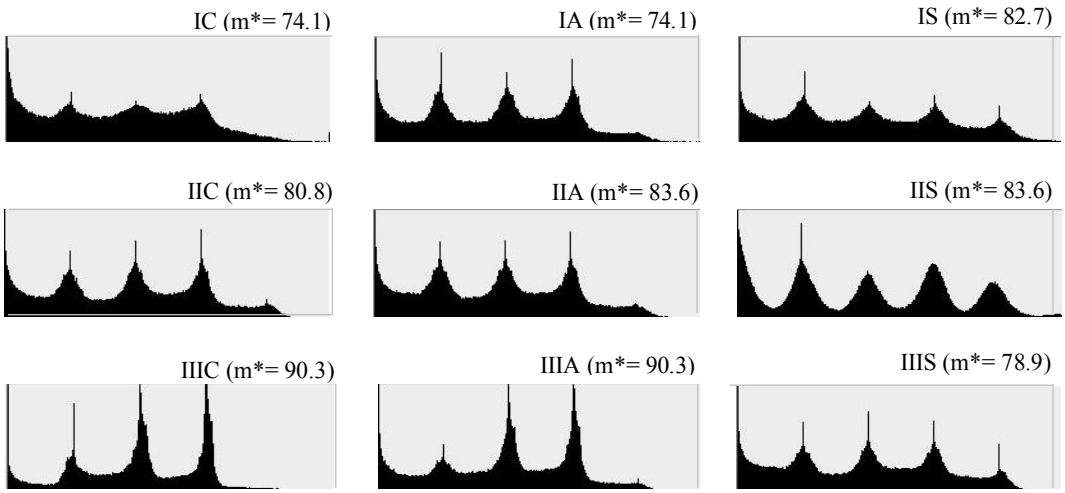
(b)		Control			Aspha-min			Sasobit		
		1	2	3	4	5	6	7	8	9
Control	1	-	S	S	N	S	S	N	S	S
	2		-	S	S	N	S	S	N	S
	3			-	S	S	N	S	S	N
Aspha-min	4				-	S	S	N	S	S
	5					-	S	S	N	S
	6						-	S	S	N
Sasobit	7							-	S	S
	8								-	S
	9									-

(c)		Control			Aspha-min			Sasobit		
		1	2	3	4	5	6	7	8	9
Control	1	-	S	S	N	S	S	N	S	S
	2		-	S	S	N	S	S	S	S
	3			-	S	S	N	S	N	S
Aspha-min	4				-	N	S	N	S	S
	5					-	S	S	S	S
	6						-	S	N	S
Sasobit	7							-	S	S
	8								-	S
	9									-

Note: Short-term oven aging conditions 1: No aging, 2: 135°C (85 min), 3: 163°C (85min)
N: non-significant, S: significant

Figure 5-14 shows the histograms of AFM 2D Images (Figures 5-7) using Photoshop Elements 7 software in order to define a quantitative value and analysis of color distribution from the images. From left to right, the histogram shows the brightness range from pure dark with the number 0 to pure white with the number 255 (x-axis) against pixels (y-axis). Therefore, the height of the "peak" at any given point shows how many pixels in a photo are at that particular brightness (Brundage 2008). According to Biro in 2005, the median value (m) in the histogram can be a characteristic of the given image. The corrected median value (m*) of color distribution, which multiplies the confidence level (0.95) into the median value, can be a representative of the digital image in terms of homogeneity. In other words, a lower m* value means a more homogeneous material. The addition of Aspha-min did not change this value in binder sources I and III while this value increased in binder source II. The addition of Sasobit to binder sources I and II showed an increase in this value while there was a decrease in binder source III. Therefore, the m* values were found to vary depending on the addition of WMA additives and the binder source from these histograms.

The hypothesis was that there might be a way to correlate the engineering properties of binders or mixtures to aging process using AFM and the above-mentioned process. For example, this technique was used to determine if any correlations existed between LMS and m* values. The results indicated that there was a stronger correlation with LMS (%) after RTFO aging (R^2 = 0.82 and 0.86), shown in Figure 5-15 and Table 5-10, than other performance properties which showed a reasonable correlation in many cases. It suggests that this procedure can be utilized to predict the engineering properties.



Note: Italics stand for binder source, m* is a corrected median value of color distribution;
C: Control, A: Aspha-min, S: Sasobit

Figure 5-14: Histograms of AFM 2D Images of SBS modified binders based on WMA additive

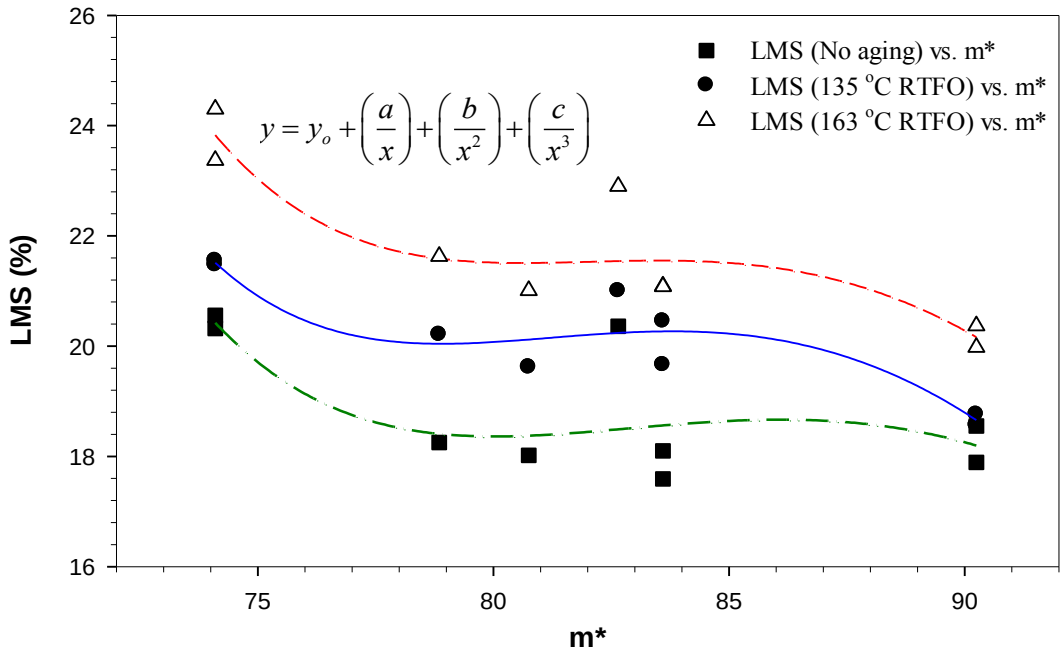


Figure 5-15: Correlations between combined LMS (%) depending on RTFO aging temperatures and m* values

Table 5-10: Coefficients and R^2 values obtained from the correlation analysis

Correlation	Coefficient				R^2
	y_o	a	b	c	
LMS (No aging) vs. m*	-1.53E03	3.87E05	-3.21E07	8.09E08	0.56
LMS (135°C RFTO) vs. m*	-2.02E03	5.01E05	-4.11E07	1.12E09	0.82
LMS (163°C RFTO) vs. m*	-2.07E03	5.10E05	-4.15E07	1.12E09	0.86

Mixture Performance Analysis

Moisture Sensitivity

ITS test is most frequently used for providing information on moisture sensitivity of HMA mixture since the presence of water often results in premature failure of pavements. It may also help to predict cracking potential, rutting, and fatigue life (Roberts 1996). The ITS in dry and wet condition and their ratio, TSR, were used as a measure of moisture sensitivity for the SBS modified asphalt mixtures. Figure 5-17 shows the dry and wet ITS values and Figure 5-16 shows the TSR values. The mixtures made with aggregate B showed relatively higher ITS values than the corresponding mixtures made with aggregate A. The combination of binder II and aggregate A had the lowest ITS values while the combination of binder II and aggregates B had the highest ITS values. Both WMA additives had a tendency to lower the ITS values in case of the mixtures made with aggregate A. Overall, the ITS values of all mixtures satisfied the requirement set forth by SC DOT (455 kPa or 65 psi). In terms of the TSR, all SBS modified asphalt mixtures resulted in TSR values higher than 85%, the criterion specified by the SC DOT, except for the mixtures made with binder II and aggregate A. The

additives seemed to increase the TSR values in the case of the mixtures made with aggregate A.

Table 5-11 indicated that the statistical differences in two additives (Aspha-min and Sasobit) were not statistically significant within each binder and aggregate source at the 5% significance level. Also, it was observed that, in most cases, there was no significant difference among wet ITS values between the control and the WMA mixtures. When compared between aggregate sources, this factor was found to have significant effect on the dry and wet ITS values of SBS modified asphalt mixtures (control, Aspha-min, and Sasobit).

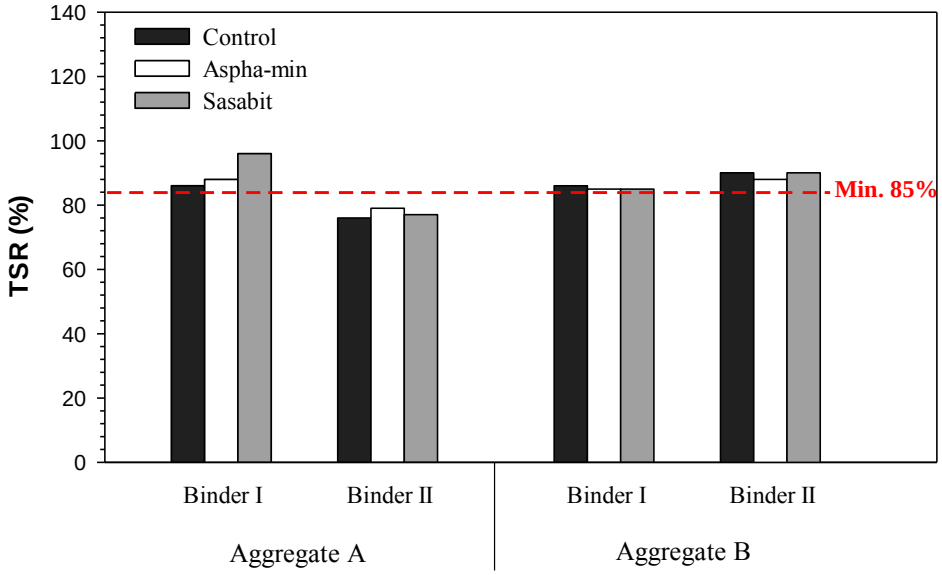
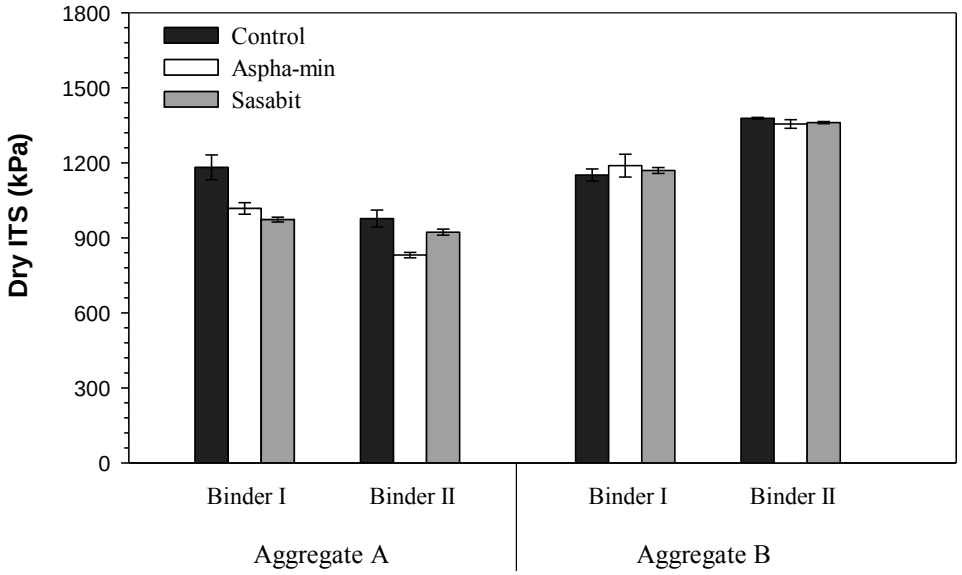
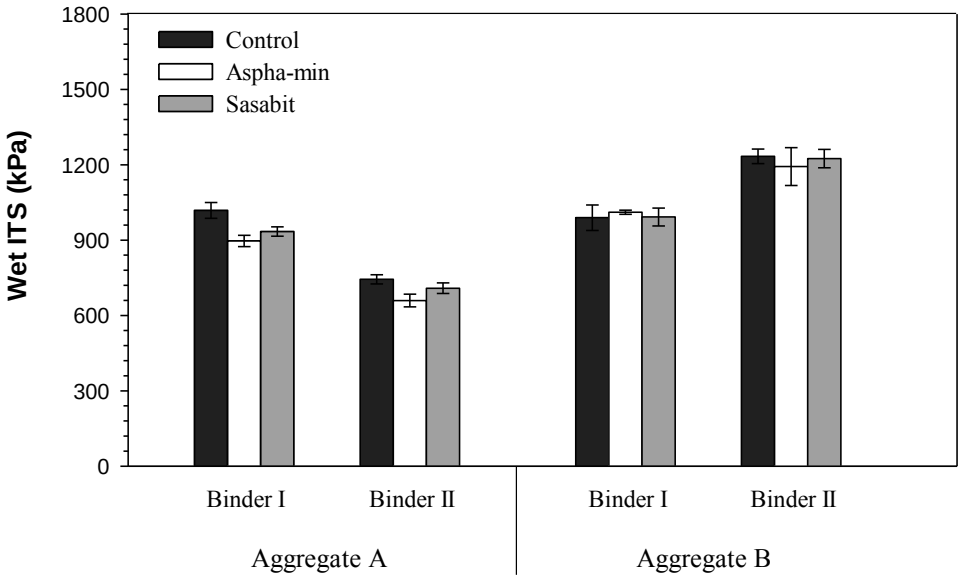


Figure 5-16: Tensile strength ratio (TSR) values of SBS modified asphalt mixtures based on WMA technology



(a)



(b)

Figure 5-17: Indirect tensile strength (ITS) values, (a) dry and (b) wet conditions, of SBS modified asphalt mixtures based on WMA technology

Table 5-11: Statistical analysis results of the ITS values of SBS modified asphalt mixtures as a function of WMA additive, binder and aggregate source (α=0.05): (a) dry ITS; (b) wet ITS.

(a)

Dry ITS			Aggregate A						Aggregate B					
			Binder I			Binder II			Binder I			Binder II		
			1	2	3	1	2	3	1	2	3	1	2	3
Aggregate A	Binder I	1	-	S	S	S	S	S	N	N	N	S	S	S
		2		-	N	N	S	S	S	S	S	S	S	S
		3			-	N	S	N	S	S	S	S	S	S
	Binder II	1				-	S	N	S	S	S	S	S	S
		2					-	S	S	S	S	S	S	S
		3						-	S	S	S	S	S	S
Aggregate B	Binder I	1							-	N	N	S	S	S
		2								-	N	S	S	S
		3									-	S	S	S
	Binder II	1										-	N	N
		2											-	N
		3												-

(b)

Wet ITS			Aggregate A						Aggregate B					
			Binder I			Binder II			Binder I			Binder II		
			1	2	3	1	2	3	1	2	3	1	2	3
Aggregate A	Binder I	1	-	S	N	S	S	S	N	N	N	S	S	S
		2		-	N	S	S	S	N	S	N	S	S	S
		3			-	S	S	S	N	N	N	S	S	S
	Binder II	1				-	N	N	S	S	S	S	S	S
		2					-	N	S	S	S	S	S	S
		3						-	S	S	S	S	S	S
Aggregate B	Binder I	1							-	N	N	S	S	S
		2								-	N	S	S	S
		3									-	S	S	S
	Binder II	1										-	N	N
		2											-	N
		3												-

Note: 1: Control, 2: Aspha-min, 3: Sasobit
N: non-significant, S: significant

Rutting Resistance

Rutting is the formation of depressions along the pavement's wheel path as a result of traffic loads. The APA test is widely used in the United States for predicting rutting potential (permanent deformation) in HMA. Figure 5-18 shows the final rut depth values for the mixtures which were compacted at an air void content of 4±0.5%. From the APA test results, the deformation values after 8000 cycles were found to be significantly below 8 mm, the recommended value (Kandhal and Cooley 2003) and even below 3 mm, the criterion specified by the SC DOT. The rut depth values of SBS modified asphalt mixtures with aggregate B were observed to be relatively lower than those with aggregate A. Sasobit were lower than the rut depths for mixture made with Aspha-min. However, the mixture made with Aspha-min, binder II, and aggregate source B showed the lowest rut depth.

The statistical results, shown in Table 5-12, revealed that the difference in the control mixtures and those made with Aspha-min was statistically insignificant within binder and aggregate source at the 5% level, indicating that the addition of Aspha-min did not have any significant effect on rutting resistance of SBS modified asphalt mixtures. The SBS asphalt mixture with Sasobit was found to have significantly different deformation in most cases. As expected, the binder and aggregate source were observed to have significant effect on rutting resistance of SBS asphalt mixtures.

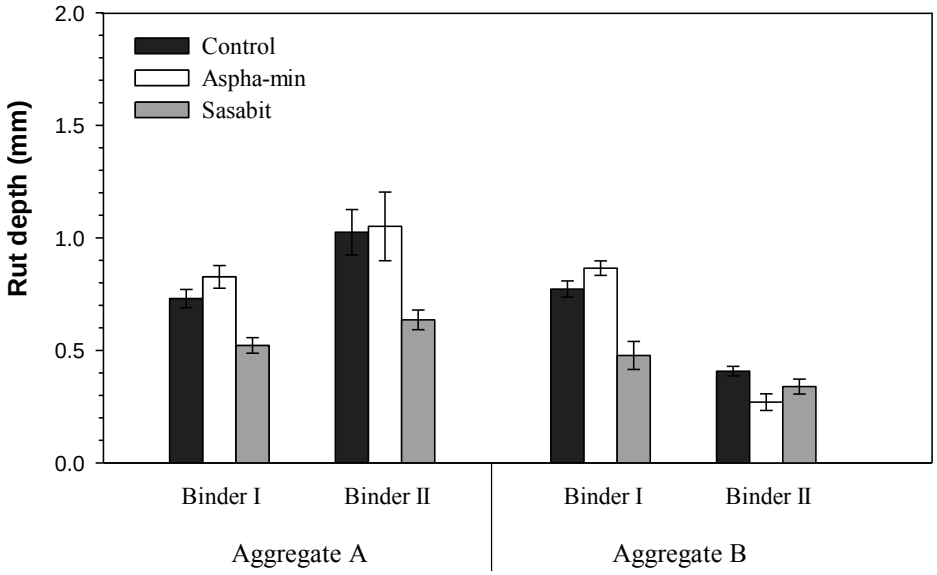


Figure 5-18: Final rut depths of SBS modified asphalt mixtures based on WMA technology

Table 5-12: Statistical analysis results of the final rut depth values of SBS modified asphalt mixtures as a function of WMA additive, binder and aggregate source (α=0.05)

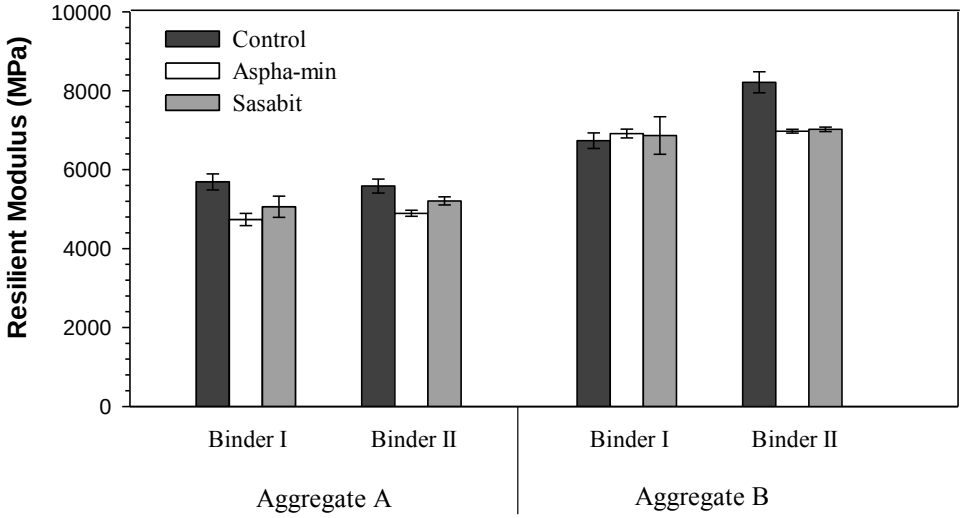
Rut depth			Aggregate A						Aggregate B					
			Binder I			Binder II			Binder I			Binder II		
			1	2	3	1	2	3	1	2	3	1	2	3
Aggregate A	Binder I	1	-	N	S	S	S	N	N	N	S	S	S	S
		2		-	S	S	S	S	N	N	S	S	S	S
		3			-	S	S	N	S	S	N	N	S	S
	Binder II	1				-	N	S	S	N	S	S	S	S
		2					-	S	S	S	S	S	S	S
		3						-	N	S	N	S	S	S
Aggregate B	Binder I	1							-	N	S	S	S	S
		2								-	S	S	S	S
		3									-	N	N	N
	Binder II	1										-	N	N
		2											-	N
		3												-

Note: 1: Control, 2: Aspha-min, 3: Sasobit
N: non-significant difference, S: significant difference

Resilient Modulus

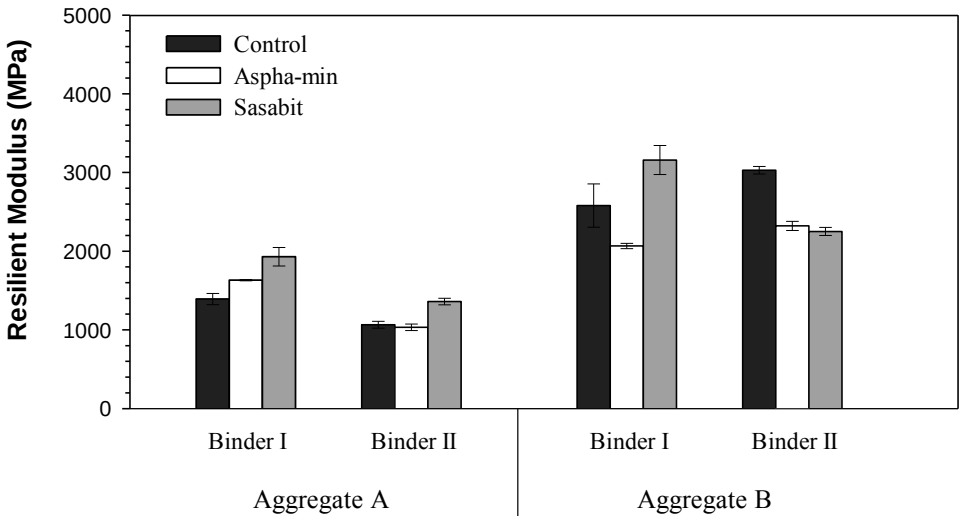
The resilient modulus typically represents the stiffness as temperature changes for asphalt mixtures. In general, a lower resilient modulus at low temperature is considered a desirable attribute from the standpoint of resistance to cracking. Inversely, a higher resilient modulus at high temperature is desired in order to have the elastic property. Figure 5-19 shows the resilient modulus at temperatures of 41, 77, and 104°F (5, 25, and 40°C). The results indicate that the mixtures manufactured with aggregate B resulted in higher resilient modulus values than those with aggregate A for all test temperatures.

Similar to the ITS and APA test results, the resilient modulus of SBS modified asphalt mixes tends to depend highly upon the aggregate sources (A or B) rather than the WMA additives (Aspha-min or Sasobit). Table 5-13 shows the percent change of resilient modulus as temperature increases. The higher rank (No.1 is the highest) means that the mixture is less sensitive to temperature and therefore is more desirable (i.e., better performance). The SBS modified asphalt mixtures made with aggregate B were observed to have less temperature sensitivity than those made with aggregate A. WMA additives generally improved the temperature sensitivity of the SBS modified asphalt mixtures, except for the mixes with aggregate B and binder II.

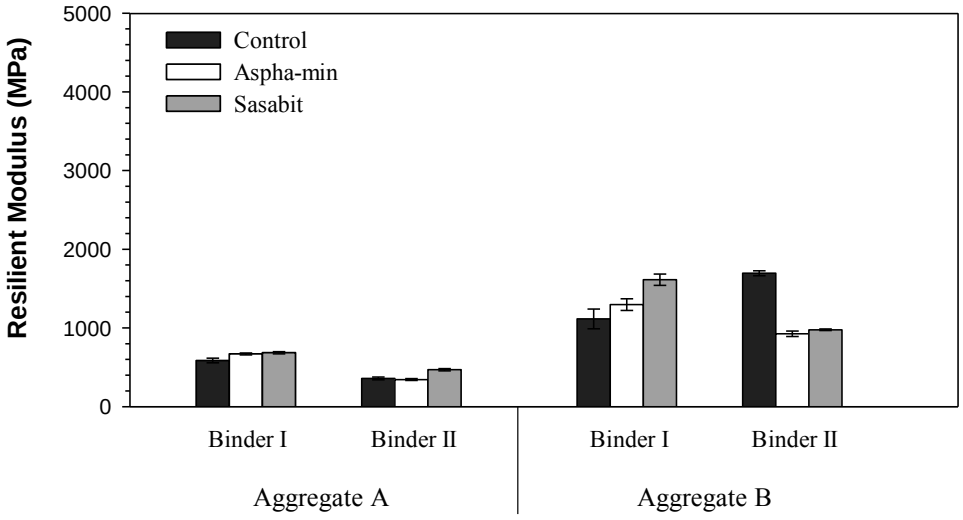


(a)

Figure 5-19: Resilient modulus of SBS modified mixtures based on WMA technology (a) 5°C, (b) 25°C, and (c) 40°C



(b)



(c)

Figure 5-19: (Continued)

Table 5-13: Change in resilient modulus (%) as temperature increases for SBS modified asphalt mixtures

	Aggregate A						Aggregate B					
	Binder I			Binder II			Binder I			Binder II		
	C	A	S	C	A	S	C	A	S	C	A	S
5 → 25°C (%)	76	66	62	81	79	74	62	70	54	63	67	68
5 → 40°C (%)	90	86	86	94	93	91	83	81	77	79	87	86
Rank	7	5	5	10	9	8	4	3	1	2	6	5

Note: C: Control, A: Aspha-min, S: Sasobit.
Rank: 1: The lowest change in resilient modulus (%) as temperature increases
10: The biggest change in resilient modulus (%) as temperature increases

ITS after long-term oven aging

Generally, the low strength values after long-term aging are considered desirable attributes from the standpoint of resistance to cracking after 10~20 years of pavement service. Figure 5-20 illustrates the ITS test results of the control and WMA mixtures which were long-term aged for 2 days at 100°C. After long-term aging, the WMA additives were observed to have no significant effects on the ITS values of SBS modified asphalt mixtures. In other words, the addition of WMA additives into SBS modified asphalt mixtures was found to have no negative influences on the stiffness properties of the SBS modified asphalt mixtures. Furthermore, material sources (aggregate and SBS modified binder) were absolutely not governed for the aged ITS values. All values, individual and average data, showed around 1,400 kPa with almost no standard error. It is hypothesized that SBS modified binders became harder and brittle around aggregates

with the accelerated aging process, and then cracking began along the harder binder films. This might offset the material source factors.

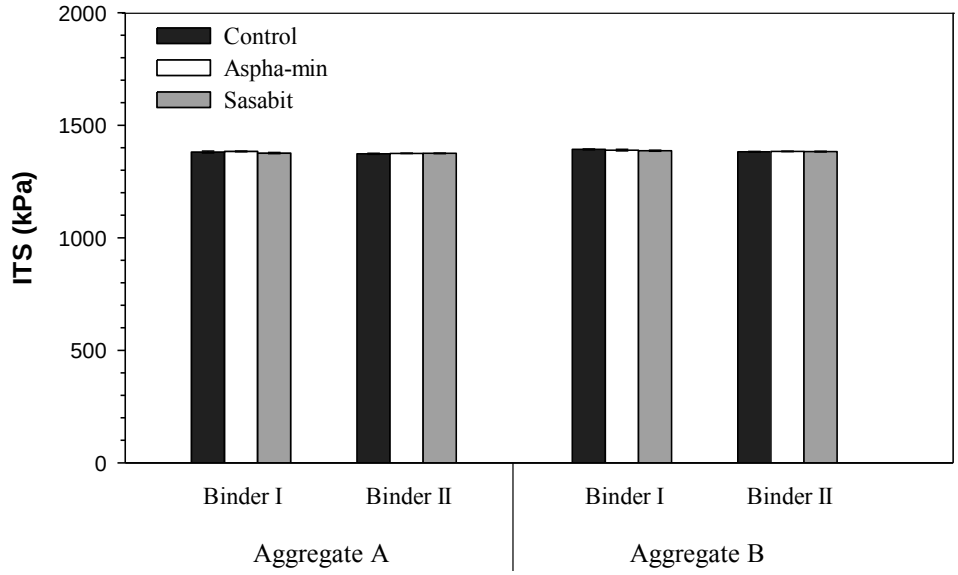


Figure 5-20: Indirect tensile strength (ITS) values of SBS modified asphalt mixtures based on WMA technology after long-term oven aging

CHAPTER SIX

SUMMARY, FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

Summary

This research was carried out primarily to determine the engineering properties of SBS modified asphalt mixtures using warm mix technologies. The basic premise was to take an established industry standard and combine it with a new technology in order to enhance the pavement product. For years, the asphalt industry has utilized polymer as a modifying agent to asphalt binder in order to improve its properties. This is in response to today's increased demands of the pavement; which include higher bearing capacities, a longer pavement life and reduced maintenance. SBS modifier has been used the most frequently for polymer modification in many parts of the world.

However, there are certain issues surrounding the use of PMA that arise from the high temperature demands and fume emissions during operations (i.e., mixing and compaction). These issues involve possible effects on human health, a negative environmental impact and the increased fuel costs. The answer to alleviating these problems may lie in the relatively new technology of WMA. The combination of WMA technology and SBS modified asphalt serves as the main concept for this research. WMA has been known to decrease the excessive temperature of HMA by working at lower temperatures using special additives or plant modifications.

This study utilized two WMA additives, micro water (Aspha-min) and synthetic wax (Sasobit) based, in order to evaluate their effectiveness in SBS modified asphalt mixtures along with binders. The first part of the study involved Superpave binder testing to investigate the performance properties (i.e., viscosity, rutting, fatigue and thermal cracking) of the SBS modified binders containing WMA additives. The surface topography of these binders was also examined using AFM in order to determine the additives' influence on various SBS modified binders. In addition, a technique was investigated to develop correlations between engineering properties of the binders (i.e., LMS values) or mixtures and the images obtained from AFM.

The second part was mainly the compaction condition study as a function of compaction levels (25 to 100 gyrations) and temperatures (154 to 96°C). This gave information detailing the behavior of WMA technology in SBS modified asphalt mixtures under these conditions. The third part investigated oxidative aging levels of SBS modified mixtures using GPC. It involved short-term oven aging (STOA) with four conditions (135°C and 154°C both for 2h and 4h). The RTFO aging was also used for comparison purposes on two aging conditions (135°C and 163°C both 85 min).

The last part was to investigate the mixture performance involving moisture sensitivity, rutting, temperature sensitivity (resilient modulus), and one long-term property (i.e., ITS after long-term oven aging). Test results were used to analyze the difference between the performance of the HMA (SBS modified asphalt mixture) and WMA (SBS modified asphalt mixture made with WMA additives). Findings and conclusions were drawn based on the analysis from the presented results.

Findings

- The addition of Sasobit significantly decreased the viscosity of the binders at 135°C due to the wax dissolution that acted like a flow improver, while the addition of Aspha-min increased the viscosity of the binders due to the remained zeolite particles after the micro water evaporated. It is important to note at this point that the benefits of Aspha-min are more evident during mixing with aggregates and not with simply binder.
- The SBS modified binders containing WMA additives resulted in higher failure temperatures than control binders, suggesting better resistance to rutting at high temperatures. Solid matters (wax crystals or zeolite particles) are thought to be contributors to its positive effects.
- WMA additives generally showed less resistance for the intermediate and low temperature properties of SBS modified binders. The addition of WMA additives resulted in having higher G*sin δ values (at 25°C) than control binders; meaning, that it was less resistant to fatigue cracking. In addition, the SBS modified binders containing WMA additives were found to have significantly higher stiffness values (at -12°C) which relate to possible low resistance on low temperature cracking. The SBS modified binders with Sasobit also showed lower *m*-values (at -12°C) than control binders.
- From the images derived from the AFM analysis, it can be seen that the addition of Aspha-min and Sasobit modified the surface topography of the binder samples. These differences also varied among binder sources as each binder source resulted

in different surface images at both the micro and Nano scales. The various properties of the SBS modified binders were believed to have an influence on the topographical results.

- A procedure, developed to correlate the engineering properties of materials to the images obtained from AFM, showed a good relationship. It suggests that this procedure might be a simple way to predict some of the engineering properties.
- Irrespective of SBS modified mixture types (i.e., HMA and WMA), the air voids decreased for all the mixtures with the increase in compaction levels (25 to 100 gyrations). All the mixtures satisfied the air voids of 4±1% requirements as per Superpave specifications at N_{design} (100 gyrations) normally adopted for high traffic volume roads.
- While working at a lower temperature (135°C), WMA mixtures yielded better compaction at 25 gyrations (at 7±1% air voids) as compared to HMA mixtures at a higher temperature (154°C).
- Statistical analysis generally showed significant differences in the air voids with respect to the compaction levels for all the mixtures indicating that compaction level plays an important role in defining the air voids for the SBS modified asphalt mixtures (HMA and WMA).
- The compaction levels were also directly related to other volumetric properties (i.e., bulk density, VMA, and VFA) and there were no noticeable differences observed in these properties between HMA and WMA mixtures. In addition,

aggregate sources were observed to be the only major indicator to influence the volumetric properties of the mixtures studied at the varying compaction levels.

- In general, for all the mixtures, it was observed that the air voids increased with decrease in the compaction temperatures (154 to 96°C). However, it was observed that the air voids of all mixtures were found to be statistically insignificant at all compaction temperatures.
- Based on the relationship between other volumetric properties (i.e., bulk density, VMA, and VFA) with respect to compaction temperatures, it was observed that WMA mixtures showed comparable results with HMA as tested for each property.
- Aging levels (i.e., LMS (%) obtained using GPC) showed a general trend that depended on time and temperature through both aging procedures (STOA and RTFO). These trends were also consistent regardless of WMA additives and SBS modified binder sources. In particular, the asphalt binder obtained from mixtures aged by the STOA procedure resulted in a higher level of aging than the asphalt binder aged by the RTFO method. The thinner binder film thickness coating the aggregates is thought to be a contributing factor.
- WMA additives (Aspha-min and Sasobit) did not largely impact the aging level of SBS modified asphalt mixtures based on the average LMS ratio obtained by the STOA procedure. Statistical results support the above finding; no significant differences were generally observed between HMA (control) and WMA mixtures with respect to the STOA conditions. The longer oven aging times (2h or 4h) may

offset the lower aging levels of the WMA mixtures when produced at lower temperatures.

- In the results of the two RTFO procedures (135°C and 163°C), lower levels of aging were clearly observed at a lower temperature than the standard temperature in all the cases and their statistical results also showed significant differences between those RTFO temperature conditions. It suggests that, using WMA technologies, age hardening can be reduced due to lower operation temperatures.
- Irrespective of WMA additives, the ITS and TSR values of SBS modified asphalt mixtures were found to be higher than 448 kPa and 85%, respectively. These values are the minimum values for wet ITS and TSR values for many DOTs around the country. In most cases, there was no significant difference of the ITS values between HMA and WMA mixtures.
- The final rut depths of all the SBS modified mixtures were much lower than the requirements specified by many DOTs (3mm). In particular, SBS modified asphalt mixtures made with Sasobit were observed to have lower rutting values, while there were no significant differences between HMA and WMA mixtures made with Aspha-min.
- The temperature sensitivity was generally improved in the SBS modified asphalt mixtures made with WMA additives based on the values obtained from the change in resilient modulus (%) values as temperature increases (5 to 40°C).

- The aggregate source seemed to have significant effect on several performance properties of the mixtures tested for this research work (i.e., moisture sensitivity, rutting resistance, and temperature sensitivity) of both HMA and WMA mixtures.
- The ITS values after long-term oven aging were found to be insignificant among all the SBS modified asphalt mixtures, regardless of the binder and the aggregate sources.

Conclusions

- WMA technologies (Aspha-min and Sasobit) can be used to decrease the compaction temperatures of SBS modified asphalt mixtures (WMA mixtures) as compared with HMA mixtures to satisfy the targeted air void contents. The fact that those WMA mixtures, especially at lower compaction levels, showed lower air voids than HMA mixtures at lower temperatures indicates that WMA technologies can help in reducing the compaction effort during the initial stages of construction.
- The lower STOA conditions, which resulted in a definite reduction of the LMS values, can be contributed to WMA mixtures. Therefore, the proposed advantage of using WMA technologies can be achieved; such as delaying the aging that takes place during hauling, placing and final compaction. Additionally, the GPC test was a relatively effective tool to quantify the aging levels of SBS modified asphalt mixtures after diverse aging conditions.

- The newly developed technique (using AFM and Photoshop histogram analysis) could be used to develop correlations among various engineering properties.
- Generally, the statistical analysis indicated that there were no significant differences between HMA and WMA mixtures regarding all engineering properties (e.g., TSR, rutting, etc.) tested for this research work. This indicates that the use of WMA technologies in SBS modified asphalt mixtures do not adversely affect the mixture properties.

Recommendations

The following topics are recommended for future research or improvement based on materials used in this study.

- Investigation of WMA field aging based on molecular size profile: Samples from various field projects (containing WMA) can be used to determine the aging process that occurs in the field. The correlation study with laboratory oven aging under various conditions is also suggested to develop the best fitting models.
- Evaluation of WMA performance with respect to compaction conditions: The performance properties (i.e., rutting and moisture damage) of WMA made under different compaction levels and temperatures can be studied.
- WMA field evaluation on the test track: Measuring the ultimate capabilities (i.e., reduced fume emissions, operations at lower temperatures, resistance to rutting, moisture damage, and cracking) of WMA in the field is suggested.

APPENDICES

Appendix A: Binder Analysis Data

Table A.1: Viscosity results of SBS modified binders at 135°C for source I

Binder Type	Trial	Viscosity (*Pa-s*)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	1st	1.513, 1.513, 1.513	1.513	0.000	0.00%
	2nd	1.538, 1.538, 1.538	1.538	0.000	0.000
	3rd	1.550, 1.563, 1.563	1.559	0.008	0.48%
	Total		1.537	0.020	1.31%
Aspha-min	1st	1.563, 1.563, 1.550	1.559	0.008	0.48%
	2nd	1.513, 1.513, 1.513	1.513	0.000	0.00%
	3rd	1.550, 1.552, 1.552	1.551	0.001	0.07%
	Total		1.541	0.022	1.40%
Sasobit	1st	1.288, 1.288, 1.288	1.288	0.000	0.00%
	2nd	1.263, 1.263, 1.263	1.263	0.000	0.00%
	3rd	1.325, 1.337, 1.337	1.333	0.077	0.52%
	Total		1.295	0.031	2.39%

Table A.2: Viscosity results of SBS modified binders at 135℃ for source II

Binder Type	Trial	Viscosity (*Pa-s*)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	1st	2.100, 2.100, 2.100	2.100	0.000	0.00%
	2nd	2.162, 2.150, 2.150	2.154	0.007	0.32%
	3rd	2.162, 2.162, 2.162	2.162	0.000	0.00%
	Total		2.139	0.029	1.38%
Aspha-min	1st	2.200, 2.200, 2.188	2.196	0.007	0.32%
	2nd	2.287, 2.287, 2.275	2.283	0.007	0.30%
	3rd	2.338, 2.338, 2.338	2.338	0.000	0.00%
	Total		2.272	0.005	0.21%
Sasobit	1st	1.850, 1.837, 1.837	1.841	0.008	0.41%
	2nd	1.888, 1.888, 1.888	1.888	0.000	0.00%
	3rd	1.875, 1.862, 1.875	1.871	0.008	0.40%
	Total		1.867	0.021	1.13%

Table A.3: Viscosity results of SBS modified binders at 135℃ for source III

Binder Type	Trial	Viscosity (*Pa-s*)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	1st	1.425, 1.425, 1.413	1.421	0.007	0.49%
	2nd	1.438, 1.438, 1.425	1.434	0.008	0.52%
	3rd	1.438, 1.425, 1.425	1.429	0.008	0.53%
	Total		1.428	0.008	0.59%
Aspha-min	1st	1.600, 1.587, 1.575	1.587	0.013	0.79%
	2nd	1.587, 1.575, 1.563	1.575	0.012	0.76%
	3rd	1.612, 1.600, 1.587	1.600	0.013	0.78%
	Total		1.587	0.015	0.95%
Sasobit	1st	1.313, 1.313, 1.325	1.317	0.007	0.53%
	2nd	1.300, 1.288, 1.275	1.288	0.013	0.97%
	3rd	1.362, 1.350, 1.350	1.354	0.007	0.51%
	Total		1.320	0.030	2.26%

Table A.4: High failure temperatures of SBS modified binders (No aging)

Binder Type	Binder Source	High Failure Temperature (℃)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	79.8, 79.2	79.5	0.42	0.53%
	II	81.7, 82.3	82.0	0.42	0.52%
	III	77.3, 77.9	77.6	0.42	0.55%
	Total		79.7	2.00	2.51%
Aspha-min	I	80.5, 79.6	80.1	0.64	0.79%
	II	83.5, 84.0	83.5	0.35	0.42%
	III	79.9, 79.8	79.9	0.07	0.09%
	Total		81.2	1.99	2.45%
Sasobit	I	79.9, 79.8	79.9	0.07	0.09%
	II	81.3, 82.9	82.1	1.13	1.38%
	III	83.5, 82.1	82.8	0.99	1.20%
	Total		81.6	1.53	1.18%

Table A.5: High failure temperatures of SBS modified binders (RTFO aging)

Binder Type	Binder Source	High Failure Temperature (°C)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	77.8, 77.8	77.8	0.00	0.00%
	II	84.3, 84.4	84.4	0.07	0.08%
	III	78.3, 77.0	77.7	0.92	0.92%
	Total		79.9	3.45	4.31%
Aspha-min	I	78.3, 78.8	78.6	0.35	0.45%
	II	84.8, 85.6	85.2	0.57	0.66%
	III	76.1, 76.3	76.2	0.14	0.19%
	Total		80.0	4.19	5.23%
Sasobit	I	82.7, 83.1	82.9	0.28	0.34%
	II	82.4, 81.8	82.1	0.42	0.42%
	III	82.1, 82.6	82.4	0.35	0.35%
	Total		82.5	0.46	0.56%

Table A.6: G*sin δ results of SBS modified binders at 25°C (PAV aging)

Binder Type	Binder Source	G*sin δ (kPa)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	4096, 4239	4167	101	2.43%
	II	2810, 2950	2880	100	3.44%
	III	1900, 1690	1775	177	9.96%
	Total		2941	1076	36.58%
Aspha-min	I	5103, 5278	5191	124	2.39%
	II	3060, 3150	3105	64	2.05%
	III	2040, 2240	2140	141	6.61%
	Total		3479	1397	40.17%
Sasobit	I	3887, 3747	3817	98	2.57%
	II	2980, 3130	3055	106	3.47%
	III	2420,2520	2470	71	2.86%
	Total		3114	0.46	19.54%

Table A.7: Stiffness results of SBS modified binders at -12℃ (PAV aging)

Binder Type	Binder Source	Stiffness (MPa)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	172, 177	175	3.54	2.03%
	II	139, 126	133	9.19	6.94%
	III	128, 124	126	2.83	2.24%
	Total		144	23.99	16.62%
Aspha-min	I	211, 213	212	1.41	0.67%
	II	174, 167	171	4.95	2.90%
	III	142, 149	146	4.95	3.40%
	Total		176	30.21	17.17%
Sasobit	I	209, 204	207	3.54	1.71%
	II	162, 169	166	4.95	2.99%
	III	172, 170	171	1.41	0.83%
	Total		181	20.10	11.10%

Table A.8: *m*-value results of SBS modified binders at -12℃ (PAV aging)

Binder Type	Binder Source	*m*-value			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	0.301, 0.300	0.301	0.001	0.24%
	II	0.332, 0.340	0.336	0.006	1.68%
	III	0.330, 0.335	0.333	0.004	1.06%
	Total		0.323	0.018	5.50%
Aspha-min	I	0.303, 0.302	0.303	0.001	0.23%
	II	0.344, 0.344	0.344	0.000	0.00%
	III	0.377, 0.339	0.338	0.001	0.42%
	Total		0.328	0.020	6.12%
Sasobit	I	0.277, 0.277	0.277	0.000	0.00%
	II	0.318, 0.321	0.320	0.002	0.66%
	III	0.269, 0.265	0.267	0.003	1.06%
	Total		0.288	0.025	8.68%

Appendix B: Compaction Condition Study Data

Table B.1: Air voids (%) results of SBS modified asphalt mixtures as a function of compaction level for aggregate A

Mixture Type	No. of Gyration	Air voids (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	25	7.6, 8.1	7.9	0.35	4.46%
	50	5.1, 5.1	5.1	0.00	0.00%
	75	4.4, 4.6	4.5	0.16	3.51%
	100	4.1, 3.9	4.0	0.11	2.85%
Aspha-min	25	7.1, 7.3	7.2	0.14	1.96%
	50	6.1, 6.1	6.1	0.00	0.00%
	75	5.7, 5.5	5.6	0.14	2.53%
	100	4.0, 4.5	4.3	0.35	8.32%
Sasobit	25	8.3,7.9	8.1	0.28	3.49%
	50	5.5, 6.4	6.0	0.64	10.7%
	75	5.2, 4.7	5.0	0.35	7.14%
	100	4.6, 4.9	4.8	0.21	4.47%

Table B.2: Bulk density (gm/cc) results of SBS modified asphalt mixtures as a function of compaction level for aggregate A

Mixture Type	No. of Gyration	Bulk density (gm/cc)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	25	2.343, 2.330	2.337	0.009	0.38%
	50	2.406, 2.406	2.406	0.000	0.00%
	75	2.425, 2.420	2.422	0.004	0.16%
	100	2.433, 2.437	2.435	0.003	0.12%
Aspha-min	25	2.351, 2.344	2.348	0.005	0.21%
	50	2.375, 2.376	2.376	0.001	0.03%
	75	2.386, 2.391	2.389	0.004	0.15%
	100	2.429, 2.414	2.422	0.011	0.44%
Sasobit	25	2.320, 2.330	2.325	0.005	0.30%
	50	2.389, 2.367	2.378	0.016	0.65%
	75	2.399, 2.409	2.404	0.007	0.29%
	100	2.412, 2.405	2.409	0.005	0.21%

Table B.3: VMA (%) results of SBS modified asphalt mixtures as a function of compaction level for aggregate A

Mixture Type	No. of Gyration	VMA (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	25	18.5, 19.0	18.8	0.35	1.89%
	50	16.3, 16.3	16.3	0.00	0.00%
	75	15.7, 15.9	15.8	0.14	0.90%
	100	15.4, 15.3	15.4	0.07	0.46%
Aspha-min	25	18.0, 18.2	18.1	0.14	0.78%
	50	17.1, 17.1	17.1	0.00	0.00%
	75	16.7, 16.6	16.7	0.07	0.42%
	100	15.2, 15.8	15.5	0.42	2.74%
Sasobit	25	19.0, 18.7	18.9	0.21	1.13%
	50	16.6, 17.4	17.0	0.57	3.33%
	75	16.3, 15.9	16.1	0.28	1.76%
	100	15.8, 16.1	16.0	0.21	1.33%

Table B.4: VFA (%) results of SBS modified asphalt mixtures as a function of compaction level for aggregate A

Mixture Type	No. of Gyration	VFA (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	25	58.7, 57.1	57.7	1.13	1.95%
	50	68.5, 68.4	68.5	0.07	0.10%
	75	71.9, 70.8	71.4	0.78	1.09%
	100	73.3, 74.1	73.7	0.57	0.77%
Aspha-min	25	60.7, 59.7	60.2	0.71	1.17%
	50	64.4, 64.5	64.5	0.07	0.11%
	75	66.1, 66.9	66.5	0.57	0.85%
	100	74.0, 71.1	72.6	2.05	2.83%
Sasobit	25	56.6, 57.9	57.3	0.92	1.61%
	50	66.6, 63.1	64.9	2.47	3.82%
	75	68.3, 70.2	69.3	1.34	1.94%
	100	70.7, 69.5	70.1	0.85	1.21%

Table B.5: Air voids (%) results of SBS modified asphalt mixtures as a function of compaction level for aggregate B

Mixture Type	No. of Gyration	Air voids (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	25	6.4, 7.1	6.8	0.51	7.51%
	50	4.8, 4.8	4.8	0.00	0.00%
	75	3.6, 3.8	3.7	0.11	2.93%
	100	3.5, 3.4	3.5	0.04	1.09%
Aspha-min	25	6.9, 6.1	6.5	0.61	9.35%
	50	4.5, 4.8	4.6	0.18	3.87%
	75	3.9, 3.5	3.7	0.32	8.81%
	100	3.4, 3.2	3.3	0.12	3.74%
Sasobit	25	6.2,6.4	6.3	0.15	2.45%
	50	6.1, 5.4	5.8	0.49	8.52%
	75	4.3, 4.6	4.5	0.17	3.84%
	100	3.8, 3.1	3.4	0.50	14.6%

Table B.6: Bulk density (gm/cc) results of SBS modified asphalt mixtures as a function of compaction level for aggregate B

Mixture Type	No. of Gyration	Bulk density (gm/cc)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	25	2.450, 2.431	2.441	0.013	0.55%
	50	2.492, 2.492	2.492	0.000	0.00%
	75	2.523, 2.519	2.521	0.003	0.11%
	100	2.527, 2.528	2.527	0.001	0.04%
Aspha-min	25	2.423, 2.446	2.434	0.016	0.65%
	50	2.485, 2.479	2.482	0.005	0.19%
	75	2.501, 2.513	2.507	0.008	0.34%
	100	2.516, 2.520	2.518	0.003	0.13%
Sasobit	25	2.453, 2.447	2.450	0.004	0.16%
	50	2.454, 2.473	2.464	0.013	0.52%
	75	2.501, 2.495	2.498	0.004	0.18%
	100	2.516, 2.535	2.526	0.013	0.52%

Table B.7: VMA (%) results of SBS modified asphalt mixtures as a function of compaction level for aggregate A

Mixture Type	No. of Gyration	VMA (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	25	16.1, 16.8	16.5	0.46	2.77%
	50	14.7, 14.7	14.7	0.01	0.00%
	75	13.6, 13.8	13.7	0.10	0.71%
	100	13.5, 13.6	13. 5	0.04	0.32%
Aspha-min	25	17.2, 16.4	16.8	0.54	3.21%
	50	15.1, 15.3	15.2	0.16	1.05%
	75	14.5, 14.1	14.3	0.29	2.02%
	100	14.0, 13.9	13.9	0.11	0.78%
Sasobit	25	16.6, 16.8	16.7	0.14	0.82%
	50	16.5, 15.9	16.2	0.44	2.70%
	75	15.1, 15.2	15.1	0.15	1.01%
	100	14.4, 13.8	14.1	0.44	3.14%

Table B.8: VFA (%) results of SBS modified asphalt mixtures as a function of compaction level for aggregate A

Mixture Type	No. of Gyration	VFA (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	25	60.2, 57.5	58.8	1.93	3.32%
	50	67.2, 67.3	67.2	0.03	0.05%
	75	73.4, 72.5	72.9	0.60	0.82%
	100	74.2, 74.5	74.3	0.21	0.29%
Aspha-min	25	59.8, 63.1	61.5	2.37	3.85%
	50	70.0, 68.8	69.4	0.86	1.24%
	75	73.0, 75.5	74.3	1.75	2.36%
	100	76.0, 77.0	76.5	0.69	0.91%
Sasobit	25	62.6, 61.8	62.2	0.61	0.99%
	50	62.9, 65.8	64.4	2.08	3.23%
	75	70.9, 69.7	70.3	0.84	1.19%
	100	73.9, 77.8	75.8	2.77	3.65%

Table B.9: Air voids (%) results of SBS modified asphalt mixtures as a function of compaction temperature at 25 gyrations for aggregate A

Mixture Type	Compaction Temperature (℃)	Air voids (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	7.6, 8.1	7.9	0.35	4.46%
	135	8.8, 8.3	8.5	0.35	4.09%
	118	8.8, 9.7	9.2	0.61	6.63%
	96	9.3, 9.0	9.2	0.16	1.76%
Aspha-min	154	7.9, 8.2	8.0	0.20	2.56%
	135	7.1, 7.3	7.2	0.14	1.96%
	118	7.9, 8.8	8.4	0.60	7.12%
	96	8.8, 10.1	9.4	0.90	9.50%
Sasobit	154	8.6, 8.6	8.6	0.00	0.00%
	135	8.3, 7.9	8.1	0.28	3.49%
	118	8.7, 8.0	8.4	0.45	5.41%
	96	8.1, 7.8	8.0	0.18	2.26%

Table B.10: Air voids (%) results of SBS modified asphalt mixtures as a function of compaction temperature at 100 gyrations for aggregate A

Mixture Type	Compaction Temperature (°C)	Air voids (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	4.2, 3.6	3.9	0.39	10.0%
	135	5.1, 4.2	4.6	0.65	14.0%
	118	5.2, 5.9	5.6	0.46	8.21%
	96	6.3, 6.0	6.1	0.19	3.16%
Aspha-min	154	4.0, 3.7	3.9	0.23	5.94%
	135	4.0, 4.5	4.3	0.35	8.32%
	118	5.2, 5.4	5.3	0.14	2.67%
	96	5.3, 5.6	5.5	0.21	3.89%
Sasobit	154	4.0, 3.2	3.6	0.52	14.4%
	135	4.6, 4.9	4.8	0.21	4.47%
	118	5.4, 5.5	5.4	0.04	0.65%
	96	6.0, 5.9	6.0	0.07	1.19%

Table B.11: Bulk density (gm/cc) results of SBS modified asphalt mixtures as a function of compaction temperature at 25 gyrations for aggregate A

Mixture Type	Compaction Temperature (°C)	Bulk density (gm/cc)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	2.343, 2.330	2.337	0.009	0.38%
	135	2.314, 2.326	2.320	0.009	0.38%
	118	2.313, 2.291	2.302	0.016	0.68%
	96	2.302, 2.307	2.305	0.004	0.18%
Aspha-min	154	2.330, 2.323	2.327	0.005	0.22%
	135	2.351, 2.344	2.348	0.005	0.21%
	118	2.329, 2.307	2.318	0.015	0.65%
	96	2.307, 2.275	2.291	0.023	0.99%
Sasobit	154	2.312, 2.314	2.313	0.001	0.05%
	135	2.320, 2.330	2.325	0.007	0.30%
	118	2.310, 2.326	2.318	0.011	0.49%
	96	2.324, 2.331	2.328	0.005	0.20%

Table B.12: Bulk density (gm/cc) results of SBS modified asphalt mixtures as a function of compaction temperature at 100 gyrations for aggregate A

Mixture Type	Compaction Temperature (°C)	Bulk density (gm/cc)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	2.387, 2.400	2.394	0.010	0.41%
	135	2.408, 2.431	2.419	0.016	0.68%
	118	2.404, 2.388	2.396	0.012	0.48%
	96	2.377, 2.384	2.381	0.005	0.21%
Aspha-min	154	2.391, 2.399	2.395	0.006	0.24%
	135	2.429, 2.414	2.422	0.011	0.44%
	118	2.397, 2.393	2.395	0.003	0.12%
	96	2.396, 2.387	2.392	0.006	0.27%
Sasobit	154	2.392, 2.411	2.402	0.013	0.54%
	135	2.412, 2.405	2.409	0.005	0.21%
	118	2.393, 2.394	2.394	0.001	0.03%
	96	2.378, 2.380	2.379	0.001	0.06%

Table B.13: VMA (%) results of SBS modified asphalt mixtures as a function of compaction temperature at 25 gyrations for aggregate A

Mixture Type	Compaction Temperature (°C)	VMA (%) results			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	18.5, 19.0	18.8	0.35	1.89%
	135	19.5, 19.1	19.3	0.31	1.69%
	118	19.6, 20.3	19.9	0.54	2.71%
	96	20.0, 19.8	19.9	0.14	0.72%
Aspha-min	154	18.7, 18.9	18.8	0.18	0.96%
	135	18.0, 18.2	18.1	0.14	0.78%
	118	18.7, 19.5	19.1	0.53	2.75%
	96	19.5, 20.6	20.1	0.79	3.94%
Sasobit	154	19.3, 19.3	19.3	0.00	0.00%
	135	19.0, 18.7	18.9	0.21	1.13%
	118	19.4, 18.8	19.1	0.40	2.09%
	96	18.9, 18.7	18.8	0.16	0.85%

Table B.14: VMA (%) results of SBS modified asphalt mixtures as a function of compaction temperature at 100 gyrations for aggregate A

Mixture Type	Compaction Temperature (°C)	VMA (%) results			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	15.3, 14.8	15.0	0.35	2.31%
	135	16.3, 15.5	15.9	0.57	3.61%
	118	16.4, 17.0	16.7	0.40	2.41%
	96	17.3, 17.1	17.2	0.17	1.00%
Aspha-min	154	15.1, 14.8	15.0	0.20	1.35%
	135	15.2, 15.8	15.5	0.42	2.74%
	118	16.4, 16.5	16.5	0.07	0.43%
	96	16.4, 16.7	16.6	0.21	1.28%
Sasobit	154	15.1, 14.4	14.7	0.46	3.11%
	135	15.8, 16.1	16.0	0.21	1.33%
	118	16.5, 16.5	16.5	0.01	0.09%
	96	17.0, 16.9	17.0	0.07	0.42%

Table B.15: VFA (%) results of SBS modified asphalt mixtures as a function of compaction temperature at 25 gyrations for aggregate A

Mixture Type	Compaction Temperature (°C)	VFA (%) results			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	58.7, 57.1	57.9	1.13	1.95%
	135	55.0, 56.6	55.8	1.10	1.98%
	118	54.9, 52.3	53.6	1.82	3.39%
	96	53.5, 54.2	53.9	0.48	0.89%
Aspha-min	154	57.9, 56.9	57.4	0.68	1.18%
	135	60.7, 59.7	60.2	0.71	1.17%
	118	57.7, 55.0	56.3	1.91	3.40%
	96	54.9, 51.2	53.0	2.62	4.93%
Sasobit	154	55.6, 55.6	55.6	0.00	0.00%
	135	56.6, 57.9	57.3	0.92	1.61%
	118	55.2, 57.3	56.3	1.45	2.58%
	96	57.1, 58.0	57.5	0.60	1.04%

Table B.16: VFA (%) results of SBS modified asphalt mixtures as a function of compaction temperature at 100 gyrations for aggregate A

Mixture Type	Compaction Temperature (°C)	VFA (%) results			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	72.5, 75.4	73.9	2.01	2.72%
	135	68.7, 73.0	70.9	3.04	4.29%
	118	68.1, 65.3	66.7	1.93	2.90%
	96	63.7, 64.8	64.3	0.77	1.20%
Aspha-min	154	73.4, 75.1	74. 3	1.18	1.59%
	135	74.0, 71.1	72.6	2.05	2.83%
	118	68.0, 67.3	67.7	0.49	0.73%
	96	67.9, 66.4	67.2	1.06	1.58%
Sasobit	154	73.7, 77.6	75.6	2.75	3.64%
	135	70.7, 69.5	70.1	0.85	1.21%
	118	67.3, 67.3	67.3	0.00	0.00%
	96	64.9, 65.2	65.1	0.21	0.33%

Table B.17: Air voids (%) results of SBS modified asphalt mixtures as a function of compaction temperature at 25 gyrations for aggregate B

Mixture Type	Compaction Temperature (°C)	Air voids (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	6.4, 7.1	6.8	0.51	7.51%
	135	7.2, 7.2	7.2	0.00	0.00%
	118	7.5, 7.9	7.7	0.32	4.13%
	96	8.9, 8.2	8.6	0.50	5.78%
Aspha-min	154	6.6, 6.5	6.6	0.04	0.64%
	135	6.9, 6.1	6.5	0.61	9.35%
	118	7.0, 6.6	6.8	0.28	4.05%
	96	7.9, 8.8	8.4	0.61	7.28%
Sasobit	154	6.8, 6.7	6.8	0.05	0.70%
	135	6.0, 6.4	6.2	0.33	5.31%
	118	7.0, 7.7	7.4	0.51	6.86%
	96	7.9, 9.1	8.5	0.88	10.3%

Table B.18: Air voids (%) results of SBS modified asphalt mixtures as a function of compaction temperature at 100 gyrations for aggregate B

Mixture Type	Compaction Temperature (°C)	Air voids (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	3.5, 3.4	3.5	0.04	1.09%
	135	3.4, 4.0	3.7	0.40	10.7%
	118	4.3, 4.2	4.2	0.02	0.45%
	96	4.5, 4.3	4.4	0.15	3.38%
Aspha-min	154	2.2, 3.0	2.6	0.53	20.3%
	135	3.4, 3.2	3.3	0.12	3.74%
	118	3.3, 3.9	3.6	0.39	10.9%
	96	4.4, 4.2	4.3	0.09	2.11%
Sasobit	154	3.6, 3.8	3.7	0.14	3.71%
	135	3.8, 3.1	3.4	0.50	14.5%
	118	3.3, 3.0	3.1	0.22	7.01%
	96	4.7, 4.1	4.4	0.39	8.95%

Table B.19: Bulk density (gm/cc) results of SBS modified asphalt mixtures as a function of compaction temperature at 25 gyrations for aggregate B

Mixture Type	Compaction Temperature (°C)	Bulk density (gm/cc)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	2.450, 2.431	2.411	0.013	0.38%
	135	2.430, 2.429	2.430	0.000	0.02%
	118	2.422, 2.410	2.416	0.008	0.35%
	96	2.384, 2.402	2.393	0.013	0.54%
Aspha-min	154	2.431, 2.433	2.432	0.001	0.04%
	135	2.423, 2.446	2.434	0.016	0.65%
	118	2.420, 2.430	2.425	0.007	0.30%
	96	2.397, 2.364	2.385	0.016	0.66%
Sasobit	154	2.437, 2.439	2.438	0.001	0.05%
	135	2.459, 2.447	2.453	0.009	0.35%
	118	2.432, 2.413	2.422	0.013	0.55%
	96	2.493, 2.507	2.500	0.010	0.41%

Table B.20: Bulk density (gm/cc) results of SBS modified asphalt mixtures as a function of compaction temperature at 100 gyrations for aggregate B

Mixture Type	Compaction Temperature (°C)	Bulk density (gm/cc)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	2.527, 2.528	2.527	0.001	0.04%
	135	2.528, 2.513	2.520	0.010	0.42%
	118	2.506, 2.507	2.507	0.001	0.02%
	96	2.500, 2.505	2.503	0.004	0.16%
Aspha-min	154	2.545, 2.525	2.535	0.014	0.55%
	135	2.516, 2.520	2.518	0.003	0.13%
	118	2.516, 2.502	2.509	0.010	0.41%
	96	2.490, 2.493	2.491	0.002	0.09%
Sasobit	154	2.520, 2.515	2.518	0.004	0.14%
	135	2.516, 2.535	2.526	0.013	0.52%
	118	2.529, 2.537	2.533	0.006	0.23%
	96	2.493, 2.507	2.500	0.010	0.41

Table B.21: VMA (%) results of SBS modified asphalt mixtures as a function of compaction temperature at 25 gyrations for aggregate B

Mixture Type	Compaction Temperature (°C)	VMA (%) results			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	16.1, 16.8	16.5	0.46	2.77%
	135	16.8, 16.8	16.8	0.00	0.10%
	118	17.1, 17.5	17.3	0.29	1.65%
	96	18.4, 17.8	18.1	0.44	2.46%
Aspha-min	154	16.9, 16.9	16.9	0.04	0.22%
	135	17.2, 16.4	16.8	0.54	3.21%
	118	17.3, 16.9	17.1	0.25	1.44%
	96	18.1, 18.9	18.5	0.54	2.93%
Sasobit	154	17.1, 17.1	17.1	0.04	0.25%
	135	16.4, 16.8	16.6	0.29	1.76%
	118	17.3, 18.0	17.6	0.45	2.55%
	96	18.1, 19.2	18.7	0.78	4.18%

Table B.22: VMA (%) results of SBS modified asphalt mixtures as a function of compaction temperature at 100 gyrations for aggregate B

Mixture Type	Compaction Temperature (°C)	VMA (%) results			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	13.5, 13.6	13.5	0.04	0.32%
	135	13.5, 14.0	13.7	0.36	2.62%
	118	14.2, 14.2	14.2	0.02	0.12%
	96	14.4, 14.2	14.3	0.13	0.93%
Aspha-min	154	13.0, 13.7	13.4	0.47	3.55%
	135	14.0, 13.9	13.9	0.11	0.78%
	118	14.0, 14.5	14.2	0.35	2.47%
	96	14.9, 14.8	14.9	0.08	0.54%
Sasobit	154	14.3, 14.5	14.4	0.12	0.85%
	135	14.4, 13.8	14.1	0.44	3.14%
	118	14.0, 13.7	13.9	0.19	1.41%
	96	15.2, 14.7	15.0	0.35	2.33%

Table B.23: VFA (%) results of SBS modified asphalt mixtures as a function of compaction temperature at 25 gyrations for aggregate B

Mixture Type	Compaction Temperature (°C)	VFA (%) results			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	60.2, 57.5	58.8	1.95	3.32%
	135	57.3, 57.2	57.2	0.07	0.12%
	118	56.2, 54.6	55.4	1.11	2.00%
	96	51.4 53.6	52.5	1.58	3.00%
Aspha-min	154	61.0, 61.2	61.1	0.16	0.27%
	135	59.8, 63.1	61.5	2.37	3.85%
	118	59.3, 60.8	60. 1	1.04	1.74%
	96	56.2, 53.4	54.8	1.97	3.60%
Sasobit	154	60.3, 60.5	60.4	0.18	0.30%
	135	63.6, 61.8	62.7	1.32	2.11%
	118	59.5, 57.0	58.3	01.8	3.09%
	96	56.4, 52.4	54.4	2.79	5.14%

Table B.24: VFA (%) results of SBS modified asphalt mixtures as a function of compaction temperature at 100 gyrations for aggregate B

Mixture Type	Compaction Temperature (°C)	VFA (%) results			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	154	74.2, 74.5	74.3	0.21	0.29%
	135	74.4, 71.3	72.9	2.21	3.03%
	118	70.0, 70.1	70.1	0.10	0.14%
	96	68.7, 69.8	69. 2	0.75	1.09%
Aspha-min	154	82.8, 78.2	80.5	3.29	4.09%
	135	76.0, 77.0	76.5	0.69	0.91%
	118	76.2, 73.2	74..7	2.15	2.88%
	96	70.8, 71.4	71.1	0.45	0.64%
Sasobit	154	74.7, 73.6	74.1	0.74	1.00%
	135	73.9, 77.8	75.8	2.77	3.64%
	118	76.6, 78.4	77.5	1.26	1.63%
	96	69.3, 72.1	70.7	1.94	2.75%

Appendix C: Oxidative Aging Analysis Data

Table C.1: LMS (%) results of SBS modified binders (No aging)

Binder Type	Binder Source	LMS (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	20.6, 20.9, 20.2	20.6	0.36	1.79%
	II	17.2, 17.9, 18.8	17.9	0.89	4.95%
	III	17.8, 17.8, 18.4	18.0	0.37	2.04%
	Total		18.8	0.54	2.91%
Aspha-min	I	20.9, 19.9, 20.2	20.3	0.51	2.50%
	II	18.4, 18.0, 19.3	18.5	0.63	3.40%
	III	18.5, 18.0, 19.3	18.1	0.77	4.27%
	Total		19.0	0.64	3.39%
Sasobit	I	20.3, 20.3, 20.5	20.4	0.09	0.42%
	II	18.7, 18.8, 17.3	18.3	0.83	4.53%
	III	17.0, 17.3, 18.4	17.6	0.73	4.17%
	Total		18.7	0.55	3.04%

Table C.2: LMS (%) results of SBS modified binders after RTFO (135°C)

Binder Type	Binder Source	LMS (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	21.2, 22.2, 21.3	21.6	0.57	2.66%
	II	19.3, 19.9, 19.7	19.6	0.32	1.65%
	III	18.5, 18.9, 19.0	18.8	0.27	1.46%
	Total		20.0	0.39	1.92%
Aspha-min	I	21.8, 21.4, 21.3	21.5	0.25	1.15%
	II	19.3, 19.8, 19.9	19.7	0.31	1.59%
	III	18.1, 18.3, 19.3	18.6	0.64	3.42%
	Total		19.9	0.40	2.06%
Sasobit	I	21.4, 20.7, 21.0	21.0	0.33	1.59%
	II	20.1, 20.7, 20.6	20.5	0.32	1.56%
	III	19.9, 20.4, 20.3	20.2	0.23	1.15%
	Total		20.6	0.29	1.43%

Table C.3: LMS (%) results of SBS modified binders after RTFO (163℃)

Binder Type	Binder Source	LMS (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	23.4, 23.6, 23.2	23.4	0.77	0.77%
	II	21.0, 20.5, 21.5	21.0	0.47	2.21%
	III	20.1, 20.2, 19.7	20.0	0.26	1.32%
	Total		21.5	0.30	1.44%
Aspha-min	I	24.6, 24.1, 24.2	24.3	0.25	1.03%
	II	21.6, 21.6, 20.6	21.1	0.49	2.32%
	III	20.0, 20.8, 20.3	20.4	0.39	1.93%
	Total		21.9	0.38	1.76%
Sasobit	I	23.0, 23.3, 22.4	22.9	0.44	1.90%
	II	21.3, 21.0, 21.0	21.1	0.17	0.78%
	III	21.3, 21.4, 22.3	21.6	0.55	2.55%
	Total		21.9	0.38	1.75%

Table C.4: LMS (%) results of SBS modified binders after STOA (135℃ for 2h)

Mixture Type	Binder Source	LMS (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	24.1, 24.4, 24.0	24.2	0.17	0.71%
	II	21.6, 22.1, 21.9	21.9	0.27	1.22%
	III	20.9, 19.9, 21.0	20.6	0.60	2.91%
	Total		22.2	0.35	1.62%
Aspha-min	I	23.8, 23.6, 24.0	23.8	0.20	0.84%
	II	22.0, 22.2, 21.6	21.9	0.30	1.36%
	III	20.9, 20.3, 20.2	20.5	0.40	1.97%
	Total		22.1	0.30	1.39%
Sasobit	I	24.4, 23.6, 22.4	24.0	0.41	1.69%
	II	20.8, 20.8, 21.7	21.1	0.51	2.44%
	III	20.9, 20.6, 21.4	20.9	0.39	1.88%
	Total		22.0	0.44	2.01%

Table C.5: LMS (%) results of SBS modified binders after STOA (135℃ for 4h)

Mixture Type	Binder Source	LMS (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	24.2, 25.1, 24.9	24.8	0.48	1.96%
	II	21.9, 22.9, 23.0	22.6	0.59	2.60%
	III	21.4, 21.3, 21.7	21. 5	0.25	1.15%
	Total		22.9	0.44	1.90%
Aspha-min	I	25.1, 24.6, 25.5	25.1	0.53	2.11%
	II	21.9, 23.0, 23.0	22.6	0.67	2.95%
	III	22.4, 21.8, 22.4	22.2	0.33	1.49%
	Total		23.3	0.51	2.18%
Sasobit	I	24.3, 24.3, 24.5	24.4	0.09	0.37%
	II	22.4, 22.7, 22.8	22.7	0.24	1.07%
	III	21.7, 21.8, 22.1	21.9	0.17	0.78%
	Total		23.0	0.17	0.74%

Table C.6: LMS (%) results of SBS modified binders after STOA (154℃ for 2h)

Mixture Type	Binder Source	LMS (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	25.0, 24.1, 24.3	24.5	0.45	1.85%
	II	22.5, 22.3, 21.4	22.1	0.63	2.85%
	III	21.7, 22.1, 21.3	21.7	0.45	2.05%
	Total		22.8	0.51	2.25%
Aspha-min	I	23.9, 24.3, 24.5	24.2	0.30	1.24%
	II	22.9, 22.2, 22.6	22.5	0.35	1.54%
	III	22.6, 22.0, 22.7	22.4	0.39	1.75%
	Total		23.1	0.51	1.51%
Sasobit	I	24.5, 24.0, 24.1	24.2	0.26	1.09%
	II	22.1, 22.0, 21.5	21.9	0.31	1.40%
	III	21.7, 21.6, 22.1	21.8	0.23	1.07%
	Total		22.6	0.27	1.19%

Table C.7: LMS (%) results of SBS modified binders after STOA (154℃ for 4h)

Mixture Type	Binder Source	LMS (%)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	24.9, 24.9, 25.1	25.0	0.10	0.41%
	II	23.7, 22.8, 23.9	23.5	0.54	2.30%
	III	23.9, 24.0, 24.2	24.0	0.13	0.53%
	Total		24.2	0.26	1.08%
Aspha-min	I	25.6, 25.4, 25.3	25.4	0.18	0.69%
	II	23.9, 23.9, 23.6	23.8	0.20	0.84%
	III	24.0, 24.0, 23.1	23.7	0.53	2.25%
	Total		24.3	0.30	1.26%
Sasobit	I	24.9, 24.6, 24.8	24.8	0.15	0.62%
	II	24.0, 23.3, 24.2	23.8	0.50	2.10%
	III	23.8, 24.6, 23.9	24.1	0.42	1.76%
	Total		24.2	0.36	1.49%

Appendix D: Mixture Performance Analysis Data

Table D.1: ITS (kPa) results of SBS modified asphalt mixtures for aggregate A

Mixture Type			ITS (kPa)			TSR (%)
			Raw Data	Mean	Standard Deviation	
Control	I	Dry	1280.7, 1124.4, 1140.7	1181.9	86.0	86
		Wet	962.0, 1020.8, 1071.8	1018.2	55.0	
	II	Dry	1035.2, 918.1, 978.8	977.4	19.0	76
		Wet	767.3, 707.3, 756.9	743.8	32.1	
Aspha-min	I	Dry	1034.4, 971.9, 1046.5	1017.6	40.1	88
		Wet	940.2, 885.0, 864.7	896.6	39.1	
	II	Dry	837.9, 845.5, 809.5	831.0	19.0	79
		Wet	706.8, 620.7, 650.3	659.3	43.7	
Sasobit	I	Dry	986.0, 953.8, 979.3	977.4	17.0	96
		Wet	900.1, 963.7, 938.4	934. 1	32.0	
	II	Dry	922.7, 901.8, 943.3	922.6	20.7	77
		Wet	668.7, 740.4, 715.8	708.3	36.5	

Table D.2: ITS (kPa) results of SBS modified asphalt mixtures for aggregate B

Mixture Type			ITS (kPa)			TSR (%)
			Raw Data	Mean	Standard Deviation	
Control	I	Dry	1189.1, 1159.2, 1106.2	1181.9	42.0	86
		Wet	1008.8, 1065.9, 893.2	989.3	88.0	
	II	Dry	1373.0, 1384.4, 1374.1	1377.8	5.9	90
		Wet	1182.6, 1282.4, 1235.2	1233.4	49.9	
Aspha-min	I	Dry	1161.2, 1277.1, 1127.2	1188.5	78.6	85
		Wet	997.0, 1011.1, 1024.9	1011.0	62.1	
	II	Dry	1380.3, 1363.1, 1321.7	1377.8	5.9	90
		Wet	1182.6, 1282.4, 1235.2	1233.4	49.9	
Sasobit	I	Dry	1192.3, 1159.7, 1155.3	1169.1	20.2	85
		Wet	970.0, 943.9, 1062.1	992.0	62.1	
	II	Dry	1352.8, 1364.5, 1360.9	1360.9	7.1	90
		Wet	1182.7, 1193.2, 1297.4	1224.4	63.4	

Table D.3: Resilient modulus (MPa) results of SBS modified asphalt mixtures for aggregate A (5℃)

Mixture Type	Binder Source	M_R (MPa)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	6588, 6360, 6560 6748, 5573, 5537 5654, 5528, 4955 4935, 4945, 4904	5091	706	12.4%
	II	4838, 4735, 4920 6233 6171, 6128 6319, 5366, 5699 5826, 5857	5183	1727	33.3%
Aspha-min	I	4711, 4550, 4633 4592, 4000, 4025 4499, 4231, 5485 5436, 5352, 5341	4738	541	11.4%
	II	4924, 4802, 4693 4823, 5329, 5116 5173, 5269, 4652 4671, 4653, 4636	4895	260	5.3%
Sasobit	I	4636, 4605, 4598 4624, 4300, 4100 4250, 4431, 6307 6307, 6376, 6218	5061	926	18.3%
	II	4882, 4875, 4908 4876, 5134, 5129 5034, 5140, 5974 5672, 5464, 5423	5209	354	6.8%

Table D.4: Resilient modulus (MPa) results of SBS modified asphalt mixtures for aggregate A (25℃)

Mixture Type	Binder Source	M_R (MPa)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	1547, 1636, 1532 1573, 1508, 1523 1559, 1581, 1126 1019, 1029, 1073	1392	247	17.8%
	II	1923, 1876, 1863 1813, 1126, 1125 1118, 1169, 1249 1243, 1143, 1141	1066	153	14.4%
Aspha-min	I	1620, 1620, 1670 1583, 1652, 1646 1635, 1631	1632	26	1.6%
	II	1060, 1055, 1071 1051, 1180, 1152 1166, 1142, 1084 1817, 1810, 1807	1033	141	13.6%
Sasobit	I	1721, 1797, 1696 1685, 1676, 1603 1545, 1557, 2364 2424, 2502, 2591	1930	408	21.1%
	II	1060, 1055, 1071 1051, 1180, 1152 1166, 1142, 1084 1817, 1810, 1807	1360	142	10.5%

Table D.5: Resilient modulus (MPa) results of SBS modified asphalt mixtures for aggregate A (40℃)

Mixture Type	Binder Source	M_R (MPa)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	626, 596, 645 654, 694, 670 660, 665, 453 451, 499, 424	587	100	17.0%
	II	280, 301, 281 271, 422, 440 396, 412, 395 356, 380	359	60	16.8%
Aspha-min	I	648, 689, 725 722, 661, 651 594, 674	670	43	6.4%
	II	308, 330, 327 306, 400, 428 407, 367, 313 303, 307, 338	345	45	13.0%
Sasobit	I	654, 673, 664 648, 639, 661 641, 642, 749 751, 756, 747	685	49	7.2%
	II	453, 486, 453 478, 443, 437 407, 383, 506 541, 535, 506	469	49	10.4%

Table D.6: Resilient modulus (MPa) results of SBS modified asphalt mixtures for aggregate B (5℃)

Mixture Type	Binder Source	M_R (MPa)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	6169, 6198, 6144 5987, 7306, 7745 7188, 7154, 4955	6736	681	10.1%
	II	8018, 8022, 8135 8240, 7475, 7265 7081, 7002, 9394 9199, 9259, 9484	8214	922	11.2%
Aspha-min	I	6680, 6579, 6510 6579, 6846, 6689 6736, 6676, 7569 7459, 7353, 7308	6915	388	5.6%
	II	7108, 7071, 7238 7081, 6795, 6725 6887, 7193, 7055 6925, 6839, 6785	6975	171	2.4%
Sasobit	I	6731, 6569, 6545 6503, 8817, 8733 8911, 9183, 5085 4944, 5188, 5164	6864	1645	24.0%
	II	7425, 6955, 6808 6887, 6817, 6928 6822, 6882, 7136 7212, 7169, 7221	7022	203	2.9%

Table D.7: Resilient modulus (MPa) results of SBS modified asphalt mixtures for aggregate B (25℃)

Mixture Type	Binder Source	M_R (MPa)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	4012, 3730, 3644 3562, 2345, 2376 2660, 2497, 1126	3103	696	22.4%
	II	3152, 2997, 2829 2978, 2909, 2780 2896, 2957, 3243 3166, 3145, 3290	3028	166	5.5%
Aspha-min	I	2213, 2319, 2072 2119, 1976, 2154 1979, 1983, 2023 2037, 1956, 1962	2066	115	5.5%
	II	2195, 2234, 2142 2134, 2133, 2246 2151, 2391, 2567 2648, 2662, 2352	2321	202	8.7%
Sasobit	I	2332, 2510, 2324 2416, 3911, 3946 3895, 3766, 3134 3336, 3162, 3162	3158	638	20.2%
	II	2508, 2381, 2418 2541, 2135, 2268 2290, 2176, 2073 2056, 2107, 2052	2250	177	7.9%

Table D.8: Resilient modulus (MPa) results of SBS modified asphalt mixtures for aggregate B (40℃)

Mixture Type	Binder Source	M_R (MPa)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	1640, 1713, 1769 1724, 1966, 1926 1982, 1923, 1730 1679, 1679, 1733	1115	435	39.0%
	II	1859, 1777, 1816 1792, 1568, 1562 1571, 1640, 1587 1785, 1684, 1704	1695	109	6.4%
Aspha-min	I	1972, 1939, 1989 1939, 1509, 1588 1479, 1511, 1382 1448, 1356, 1459	1298	257	19.8%
	II	1890, 1754, 1807 1841, 1884, 1857 1930, 1869, 1155 1114, 1010, 1002	926	122	13.1%
Sasobit	I	1765, 1631, 1823 1704, 1845, 1706 1864, 1851, 1254 1254, 1302, 1354	1613	249	15.4%
	II	1986, 1922, 1933 1951, 1958, 1937 1971, 1994, 1027 1012, 1028, 1009	977	37	3.8%

Table D.9: Rut depth (mm) results of SBS modified asphalt mixtures for aggregate A

Mixture Type	Binder Source	Rut depth (mm)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	0.90, 0.98, 0.78 0.96, 0.69, 0.60 0.63, 0.65, 0.64 0.65, 0.60, 0.68	0.73	0.14	19.2%
	II	1.50, 1.58, 1.21 0.88, 1.24, 0.72 0.80, 0.81, 1.45 0.77, 0.61, 0.73	1.03	0.35	33.9%
Aspha-min	I	0.71, 0.74, 0.74 0.71, 1.09, 1.07 0.67, 1.09, 0.69 0.68, 0.98, 0.75	0.83	0.17	21.1%
	II	1.69, 1.40, 0.70 0.53, 1.75, 1.34 0.48, 0.73, 1.66 1.33, 0.70, 0.30	1.05	0.53	50.2%
Sasobit	I	0.51, 0.67, 0.61 0.54, 0.61, 0.32 0.60, 0.49, 0.40 0.31, 0.58, 0.62	0.52	0.12	23.0%
	II	0.73, 0.62, 0.73 0.52, 0.43, 0.64 0.41, 0.54, 0.87 0.61, 0.89, 0.64	0.64	0.15	23.9%

Table D.10: Rut depth (mm) results of SBS modified asphalt mixtures for aggregate B

Mixture Type	Binder Source	Rut depth (mm)			
		Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	I	0.71, 0.63, 0.92 0.80, 0.70, 0.62 0.95, 0.64, 0.90 0.94, 0.71, 0.75	0.77	0.13	16.2%
	II	0.32, 0.48, 0.39 0.42, 0.28, 0.38 0.54, 0.48, 0.37 0.40, 0.37, 0.46	0.41	0.07	17.9%
Aspha-min	I	0.89, 0.78, 0.64 0.68, 0.86, 0.91 0.90, 0.94, 0.98 0.95, 0.99, 0.86	0.87	0.11	12.9%
	II	0.31, 0.35, 0.58 0.27, 0.20, 0.10 0.17, 0.28, 0.16 0.35, 0.17, 0.30	0.27	0.13	47.0%
Sasobit	I	0.74, 0.78, 0.30 0.32, 0.78, 0.77 0.37, 0.34, 0.31 0.32, 0.34, 0.36	0.48	0.22	45.1%
	II	0.50, 0.59, 0.42 0.32, 0.20, 0.25 0.23, 0.29, 0.28 0.29, 0.39, 0.31	0.34	0.12	34.1%

Table D.11: ITS (kPa) after long-term oven aging results of SBS modified asphalt mixtures

Mixture Type			ITS (kPa)			
			Raw Data	Mean	Standard Deviation	Coefficient of Variation
Control	A	I	1388.7, 1376.6, 1377.6	1380.9	6.7	0.49%
		II	1368.6, 1373.2, 1377.1	1372.9	4.3	0.31%
	B	I	1395.8, 1392.5, 1389.7	1392.7	3.1	0.22%
		II	1384.4, 1378.9, 1382.5	1382.0	2.8	0.20%
Aspha-min	A	I	1386.3, 1380.8, 1384.2	1383.8	2.8	0.20%
		II	1373.7, 1375.5, 1375.0	1374.8	1.0	0.07%
	B	I	1391.5, 1393.4, 1382.5	1389.1	5.8	0.42%
		II	1382.7, 1385.2, 1383.0	1383.6	1.4	0.10%
Sasobit	A	I	1377.9, 1379.5, 1370.6	1376.0	4.7	0.34%
		II	1374.4, 1373.3, 1376.9	1374.9	1.8	0.13%
	B	I	1391.5, 1383.5, 1385.7	1386.9	4.1	0.30%
		II	1385.2, 1380.2, 1383.2	1382.9	2.6	0.19%

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